

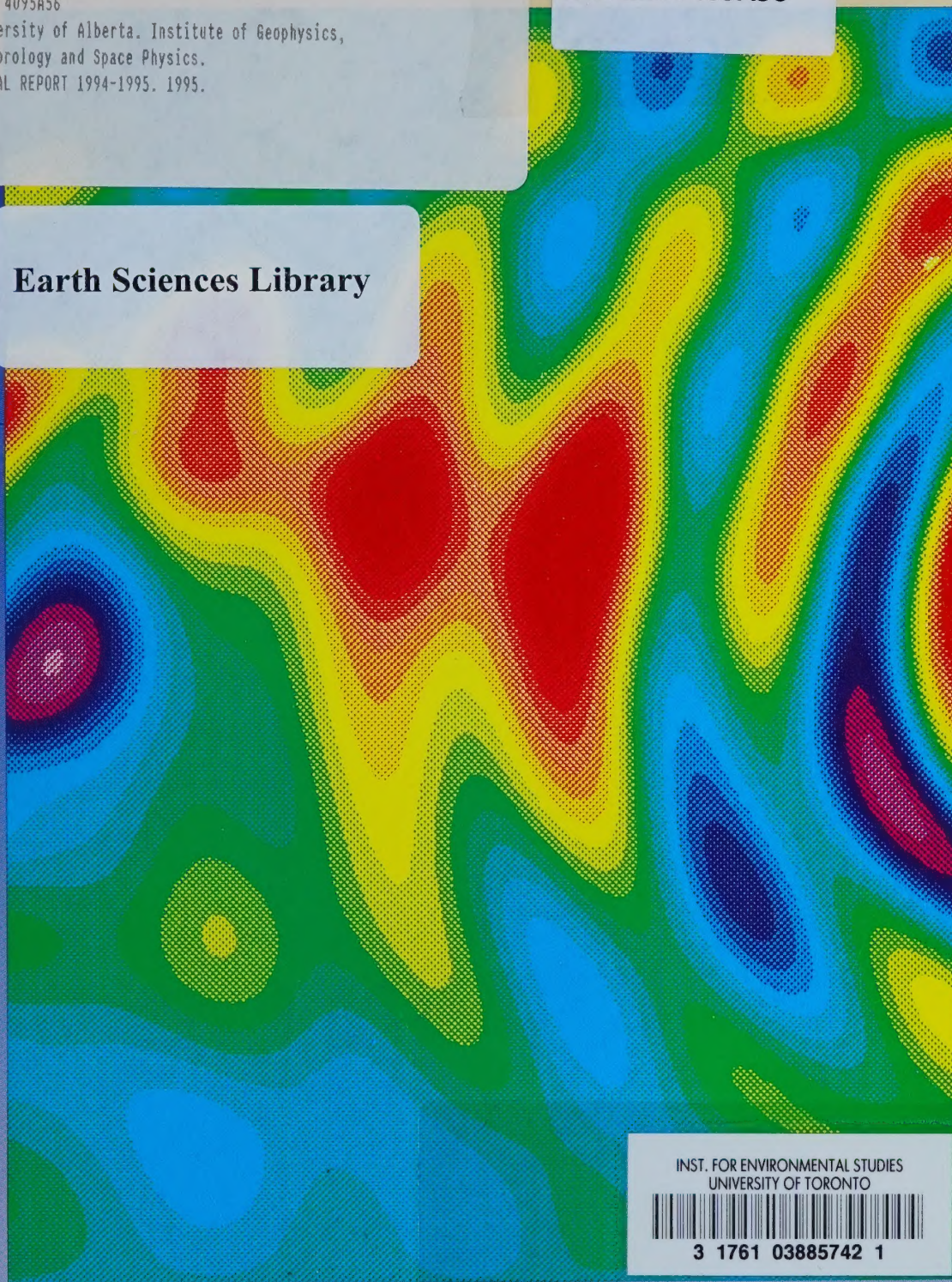
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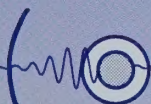
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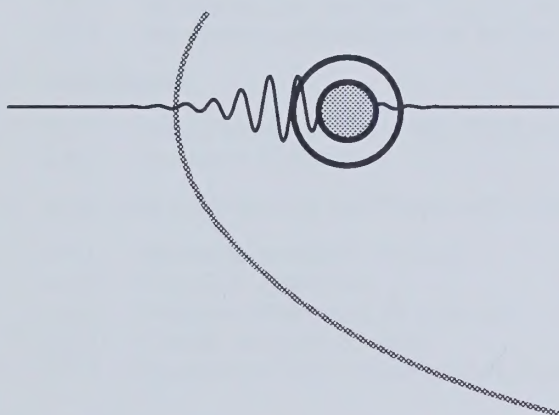
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INSTITUTE OF GEOPHYSICS, METEOROLOGY & SPACE PHYSICS

ANNUAL REPORT

1994-95



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Cover: The front cover depicts a horizontal section of the pressure field associated with a numerical simulation of an unstable steadily-travelling three-dimensional eddy decaying into a train of Rossby waves in a rotating periodic channel with a sloping bottom. The remains of the counter-clockwise rotating eddy is the blue/grey coloured circular blob seen near the left side of the panel. The Rossby wave tail is the crescent shaped region coloured red/yellow. Blue tones correspond to low pressure and red tones correspond to high pressure anomalies, respectively. The eddy is moving from left to right and the Rossby wave field is produced due to the production of vorticity due to vortex-tube stretching associated with the passage of the eddy in a stratified fluid. (Picture courtesy of Gordon Swaters).

1. Council of the Institute

Ex Officio Members

Murray R. Gray, BAsC (Toronto) MEng (Calgary) PhD (California Institute of Technology) Professor of Chemical Engineering, Dean of Graduate Studies and Research

Brian Jones, BSc (Liverpool) PhD (Ottawa) Professor and Chair, Department of Earth and Atmospheric Sciences

Martha C. Piper, MA (Connecticut) PhD (McGill) Professor of Physical Therapy and Pediatrics, Vice-President (Research)

Richard E. Peter, BSc (Alberta), PhD (Washington) Professor of Zoology and Dean of Faculty of Science

Sherman D. Riemenschneider, MA PhD (Syracuse) Professor and Chair, Department of Mathematical Sciences

John Shaw, PhD (Reading), Professor and Chair, Department Geography

Executive Members

Edward P. Lozowski, MSc, PhD (Toronto), Director of the Institute of Geophysics, Meteorology & Space Physics, and Professor of Earth and Atmospheric Sciences

Michael E. Evans, MSc (Birmingham), PhD (Australian National University), Associate Director of the Institute of Geophysics, Meteorology and Space Physics, and Professor of Physics

Ernest R. Kanasewich, MSc (Alberta), PhD (British Columbia) FRSC, Chairman of Department of Physics, Associate Director of the Institute of Geophysics, Meteorology & Space Physics, and Professor of Physics

Gordon Rostoker, MA (Toronto), PhD (British Columbia), Associate Director of the Institute of Geophysics, Meteorology & Space Physics, and Professor of Physics

Gordon E. Swaters, PhD (British Columbia), Associate Director of the Institute of Geophysics, Meteorology & Space Physics, and Professor of Mathematical Sciences

and all permanent members of the Institute of Geophysics, Meteorology & Space Physics

Faculty Members

Robert A. Creaser, PhD (La Trobe) Assistant Professor of Earth & Atmospheric Sciences

John Gray, PhD (McMaster), Professor of Physics

Frantisek Hron, D. Nat. Sci. (Charles), Professor of Physics

F. Walter Jones, PhD (McGill), Professor of Physics

Robert Luth, PhD (UCLA), Associate Professor of Earth & Atmospheric Sciences

Roger D. Morton, PhD (Nottingham), Professor of Geology

Edo Nyland, PhD (UCLA), Professor of Physics

Gerhard Reuter, PhD (McGill), Associate Professor of Earth & Atmospheric Sciences

Jim S. Rogers, PhD (Alberta), Professor of Physics

Wojciech Rozmus, PhD (Inst. of Nuclear Res., Poland) Professor of Physics

John C. Samson, PhD (Alberta), Professor of Physics

Douglas R. Schmitt, PhD (Caltech), Associate Professor of Physics

Martin J. Sharp, PhD (Aberdeen), Associate Professor of Earth & Atmospheric Sciences

John Shaw, PhD (Reading), Professor and Chair, Department of Geography

Samuel S. Shen, PhD (Wisconsin), Associate Professor of Mathematical Sciences

T.J. Tim Spanos, PhD (Alberta), Professor of Physics,

John D. Wilson, MSc (Alberta), PhD (Guelph), Professor of Earth & Atmospheric Sciences

2.1 Professors Emeriti

Keith D. Hage, PhD (Chicago)

David Rankin, PhD (Alberta)

Erhard R. Reinelt, PhD (Alberta)

2.2 Research Associates

Przemek Frycz, PhD (Warsaw)

Liang Gong, PhD (Alberta)

W. William Liu, PhD (Rice)

Robert Rankin, PhD (North Wales)

Krzysztof Szilder (Krakow)

Yves Thibault PhD (Alberta) (to September 1994)

Vladimir Tikhonchuk, PhD (Moscow Engineering Physics Institute)

Chang-Quan Wei, PhD (Alaska) (to September, 1994)

2.3 Postdoctoral Fellows

Alex MacAulay, PhD (Princeton)

Michael Burianyk, PhD (Alberta)

Nozomu Nishitani, PhD (Nagoya) (to April 1994)

Norman Udey, PhD (Alberta)

2.4 Technical Staff

Hamid al Nashi, Computer Technician (from January, 1995)

Karen S. Apps, Computer Technician (to February, 1995)

Sherwood Botsford, System Administrator

Sarah Derr, Research Assistant

Diane Caird, Technologist

Jean-Pierre DeVilliers, Programmer (to August, 1994)

Rafal Dymarz, Systems Analyst

Elizabeth C. Tooley, Research Assistant

Susan H. Skone, Research Assistant (from June 1994)

Laura Smith, Secretary, Meteorology

2.5 Graduate Students

PhD Department of Geography

Ryan Blackmore
Zhigang Shi
Lingyan Xin

PhD Department of Geology

David Hauth
S. Trupia

M.Sc. Department of Mathematical Sciences

Francis Poulin
Matt Reszka
Xiaochun Wang

PhD Department of Mathematical Sciences

Vlad Agapov
Richard Karsten
Yuanjie Yang

MSc Department of Physics

Tim Nyitrai
Lei Wei
Hu-Shun Zhou

PhD Department of Physics

Martin G. Connors
Peter Damiano
Frances Fenrich
Erena Friedrich
Jeremy Gallop
Ahmed Kebaili
Jason Myatt
Stephane Nechtschein
Ivan Ourdev
Alex Tsemahman
Igor Voronkov
Dongsong Yang

Course Based Masters Completed: Physics

Gilbert Dubuc

MSc Completed: Mathematical Sciences

- Curtis J. Mooney "Finite amplitude baroclinic instability of a mesoscale gravity current in a channel"
- Patrick G. Timco "Turbulent dissipation of internal solitons"
- Carol G. Slomp "On the Hamiltonian structure, stability characteristics and finite amplitude evolution of geostrophic fronts"

MSc Completed: Meteorology

- Raymond Beaubien "Radar Observations of Precipitation Production in Alberta Snowbands"
- Bruno Larochelle "Applications of the Synthetic Dual-Doppler Technique to an Operational Doppler Weather Radar"
- Daryl O'Dowd "Investigation of Ice Nuclei from the Industrial Complex of Exshaw, Alberta"
- Russell Sampson "Atmospheric Refraction and its Effects on Sunrise and Sunset"
- Brian Wiens "A Study of Nocturnal Drainage Flows in Relation to Woodsmoke Pollution in a Valley"

MSc Completed: Physics

- Ralf Oppitz "Nonlinear Evolution of Stimulated Brillouin Scattering in an Inhomogeneous Plasma"
- Li Jiang "Identification of Magnetic Minerals in Archaeomagnetic Samples"
- Lu Rong "Seismic Reflection Evidence for Paleozoic and Precambrian Tectonic Activity in East Central Alberta"

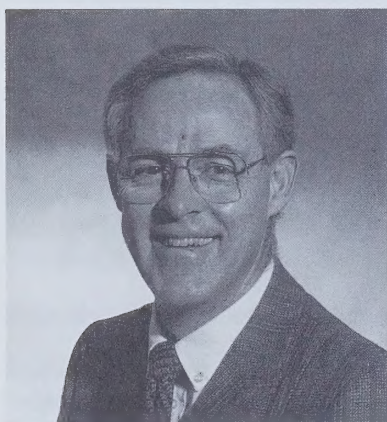
PhD Completed: Physics

- Michael Buriandyk "Lithosphere in BC and Alberta from Seismic Experiments"

PhD Completed: Meteorology

- Victor Chung "Ship Icing and Stability"
- Shuming Du "Stochastic Models for Turbulent Diffusion"
- Shucai Guan "Numerical Simulation of the Effects of Industrial Complexes on Convective Rain Showers"

3. Director's Report



E.P. Lozowski

The Institute of Geophysics, Meteorology and Space Physics embraces a membership of 22 continuing faculty members, 3 professors emeriti, 13 research associates, 18 postdoctoral fellows, 22 PhD students and 17 MSc students. Our membership spans four departments (12 in Physics, 2 in Mathematics, 3 in Geology and 5 in Geography). As of July 1, 1995 this was reduced to three departments when the departments of Geology and Geography are merged to become the Department of Earth and Atmospheric Sciences. The Executive consists of the Director and four Associate Directors. This year Dr. John Wilson stepped down as Associate Director and was replaced by Dr. Gordon Swaters. We thank John for his service, especially with the seminar series.

Dr. Gordon Rostoker stepped down as Chair of the Advisory Board for the Herzberg Institute of Astrophysics of the National Research Council. He has been appointed as Chair of the NSERC Grant Selection Committee for Astronomy and Space Physics for 1994-1995. He also continues as Chair of the Solar-Terrestrial Energy Program (STEP), the flagship scientific program of the Scientific Committee for Solar-Terrestrial Physics (SCOSTEP). He has recently been appointed to the Solar-Terrestrial Advisory Committee (STRAC) of the Canadian Space Agency. While the Canadian Network for Space Research wound down, the Canadian Space Agency provided transitional funding for young researchers. In a competition, the three Research Associates with the Space Physics group, Drs Robert Rankin, William Liu and Przemek Frycz, were all awarded contracts to continue their research at the University of Alberta for the next three years.

Dr. Ted Evans was an invited keynote speaker at a conference entitled "Paleomagnetism of the Mediterranean area" organized by the Geological Society of London, England. He also gave two invited talks (co-authored with Prof. F. Heller, ETH, Zürich, Switzerland) at the European Geophysical Society Meeting in Hamburg. Dr. John Wilson has joined the Editorial Board of "Agricultural and Forest Meteorology" and continues on the Editorial Board of "Boundary-Layer Meteorology". Research Associate in Geography, Dr. Krzysztof Szilder, was awarded a Japan Society for the Promotion of Science Fellowship to collaborate with Dr. Kimiteru Sado at the Kitami Institute of Technology.

Dr. Edo Nyland travelled to India to participate in aspects of the International Lithosphere Projects. He is also very much involved in questions of the use of technology in alternative educational delivery methods here on campus. Drs. Wilson and Rozmus were promoted to Full Professor this year and Drs. Luth and Reuter were promoted to Associate Professor. Dr. Swaters was awarded the Canadian Meteorological and Oceanographic Society's President's Prize. It is indeed a pleasure to note that the Institute seems to have established a "McCalla Professorship Tradition", Dr. Samson having been awarded one in 1993, Dr. Rozmus in 1994 and Dr. Swaters in 1995. Dr. Szilder and Dr. Lozowski received a Best Paper Award at the 1995 Conference of the International Society for Offshore and Polar Engineering in the Hague.

The Institute Library has now been moved to a new, brighter and more comfortable location just to the east of the main office. Several new titles have been added to the collection. We are in the process of acquiring a new computer which will augment this store of hardcopy information, by enabling institute members and students to access geophysical, meteorological and space information on CD ROM and on the Internet. Thanks to the efforts of Ms. Gloria Reese, the Institute Secretary, and Mr. Jim MacKinnon, Systems Analyst for Physics, the Institute has become one of the first organizations on campus to have its own Worldwide Web home page (<http://edmobobs.phys.ualberta.ca/>). The home page is still "under construction" but it provides access to the text of the latest Annual Reports. As the WWW becomes more generally accessible, and as our ability is enhanced to produce and disseminate multimedia documents on it, the Institute may in future produce its Annual Report entirely electronically. For the present however, we have chosen to pursue both the traditional hardcopy as well as the electronic publication formats. The 1993-1994 report grew to 74 pages and included color endplates and a color cover.

Plans for fundraising for the Institute are at the stage of identifying collaborative projects on which we can embark, and identifying appropriate funding sources for these projects. The Institute Library recently acquired the titles "The 1995 Canadian Oil Industry Directory" and "The Directory of Corporate Giving in Canada 1994/95", as a guide to matching potential projects with resources. One proposal which has been put forward is the sponsorship of an ongoing distinguished seminar series on climate change. Towards this end, the Director is currently involved with Alberta Environment, the Canadian Energy Research Institute and the Clean Air Strategic Alliance in organizing an Alberta Symposium on Climate Change to be held in the Fall of 1995. Since it will target an industry audience, it will likely be held in Calgary, but the Institute plans to bring some of the scientific speakers to Edmonton to offer seminars at the University of Alberta as well.

Last but by no means least, we were extremely pleased to learn this year that the founding director of the Institute, Dr. Jack Jacobs, was awarded the American Geophysical Union's Adam Fleming Medal. The Fleming Medal recognizes original research and technical leadership in geomagnetism, atmospheric electricity, aeronomy, and related sciences.

4. Visitors to the Institute

Rama Agarwal	Ottawa
Joe H. Allen	SCOSTEP, Boulder, CO
C. Anger	ITRES Research
Leroy Cogger	University of Calgary
F. Creutzberg	NRC/HIA, Ottawa, ON
Roger Daley	Atmospheric Environment Service
George Eynon	CSPG, Calgary
Vladimir Fiala	Institute of Atmospheric Physics, Prague
D.W. Green	University of Calgary
Friedrich Heller	Inst. Geophysics, ETH Zurich
George Isaac	Atmospheric Environment Service
David Kendall	Space Science Program CSA, Ottawa
F.E.M. (Ted) Lilley	Research School of Earth Sciences, Australian National University, Canberra
Larry Lines	Memorial University, Newfoundland
R.P. Lowe	University of Western Ontario
Ian McDiarmid	Ottawa
Don McEwen	University of Saskatchewan (CNSR)
Peter Moczo	Geophysical Institute Slovak Academy of Sciences
Luo Ping	Chinese National Petroleum Corp.
Balkrishna Sapkota	Dept. of Physics, IOE, Nepal
Robert Schemenauer	Environment Canada
Rick Schwartzberg	NSERC
Li Xiu Sheng	CNPC
Gordon Shepherd	York University (CNSR)
George Sofko	University of Saskatchewan (CNSR)
Martin Stellmacher	Institute of Geophysics, Tech University, Braunschweig, Germany

Brian Tinsley	Centre for Space Science, Univ. of Texas at Dallas
David Wardle	Environment Canada
Colin Waters	Department of Physics, University of Newcastle, NSW, Aust.
Wei Zhang	CNPC

Seminars

Michael Burianyk	"The analysis and interpretation of wide-angle seismic profiles for Lithospheric studies"
Antonio Correia	"Results of a magnetotelluric survey performed in southern Portugal"
Roger Daley	"Recovery of the windfield from atmospheric chemical constituent observations using data assimilation methods"
George Eynon	"Geoscientists in oil and gas: global factors affecting Canada's oil and gas industry, the changing role of the geoscientist, and emerging employment trends"
George Isaac	"Aircraft icing at the airport and in-flight"
Kwang-Y Kim	"Comparisons of the second-moment statistics of climate models"
Ted Lilley	"Mohr circles in magnetotelluric analysis"
	"A bicentenary in geomagnetism: the d'Entrecasteau expedition 1791-1793"
Larry Lines	"Depth imaging of seismic data from structurally complex areas"
Peter Moczo	"Effects of surface geology on earthquake ground motion"
Edo Nyland	"India and the International Lithosphere Project"
Robert Schemenauer	"A broad look at precipitation and fog deposition"
Brian Tinsley	"Solar wind modulation of the global electric circuit, and apparent consequences for weather and climate change"
A. Tsemahman	"Linear iterative inversion of VSP field data"

5. Courses in Geophysics, Meteorology and Space Physics

It is possible for students to take Honours in Geophysics, or a four-year professional degree in Geophysics. It is also possible to study Meteorology as a subject of concentration. Graduate work in Geophysics may be undertaken in the Department of Physics, and in Meteorology in the Department of Earth and Atmospheric Sciences. Details of courses, and of requirements for admission to them may be found in the Arts and Sciences Calendar in the case of undergraduate courses, and in the Graduate Studies Calendar in the case of post-graduate courses.

Undergraduate Courses (Department of Physics)

Geophysics 221 - *Physics of the Earth*

The solar system, its origin and the abundance of elements. Meteorites. Elements of seismology. Properties of the Earth's interior. Gravity and the shape of the Earth. Heat flow and thermal history of the Earth. Geomagnetism, aeronomy, magnetosphere and interplanetary space.

Geophysics 227 - *Seismic Exploration Methods*

Elastic properties of rocks. Geometric rays. Application of seismic refraction and reflection methods. Interpretation of seismic sections. Sonic Logging.

Geophysics 229 - *Geophysical Prospecting*

Application and interpretation of gravitational, magnetic and electromagnetic and radiometric prospecting methods. Theory of well logging. Geothermal properties of the Earth.

Geophysics 325 - *Gravity, Magnetic and Electrical Prospecting Techniques*

Elementary potential theory as required for gravity, magnetic and electrical studies of the Earth's crust. Gravimeters and magnetometers; magnetic and electrical properties of rocks; well logging methods; induced polarization.

Geophysics 326 - *Ray Seismology*

Use of seismic refraction and reflection methods for exploration of petroleum and ground water. Elasticity theory, seismic instrumentation, velocity surveys, near surface corrections.

Geophysics 421 - *Seismology and Physical Structure of the Earth*

Seismology; infinitesimal strain theory; elastic stress and moduli of media; earthquake mechanisms; physical structure of the Earth; seismometers.

Geophysics 424 - *Electromagnetic and Potential Methods of Exploration*

Theory and application of Maxwell's equations. Potential theory as applied to gravity, magnetic and electrical studies. Interpretation of field data. Direct and indirect methods of inversion to obtain model structures.

Geophysics 426 - *Time Series in Applied Seismology*

Application of time series analysis to seismic data processing. Fast Fourier Transforms; Z transformation, spectral analysis, bandpass and velocity filtering, deconvolution, auto and cross correlation; analog to digital conversion, wave propagation in layered media.

Geophysics 429 - *Upper Atmosphere and Space Physics*

Generation of the solar wind; the interplanetary plasma and field environment; the solar-terrestrial interaction; magnetospheric substorms; the aurora borealis; magnetosphere-ionosphere interactions; effect of magnetospheric storms on man-made systems; use of natural electromagnetic fields for geophysical exploration.

Geophysics 429 - *Application of Methods in Environmental and Exploration Geophysics*

Field trip held before and during fall term provides electrical, electromagnetic, gravitational and magnetic data sets for analysis during term.

Geophysics 438 - *Aspects of Seismic Data Processing*

A previously acquired seismic data set will be corrected, enhanced and imaged in a computer workstation laboratory.

Undergraduate Courses (Department of Geography)

Geography 333 - *Physical Climatology*

An examination of the processes influencing climate on the global, regional and local scales.

Geography 433 - *Microclimatology*

Introduction to the physical processes determining microclimate.

Meteorology 220 - *Meteorological Instrumentation*

Laboratory work and lectures to develop skills in environmental measurement.

Meteorology 230 - *Introduction to Meteorology*

A systematic study of weather elements and atmospheric processes with emphasis on underlying physical principles.

Meteorology 330 - *Atmospheric Physics I*

Principles of thermodynamics, thermodynamic diagrams, convection, solar and terrestrial radiation.

Meteorology 331 - *Introduction to Atmospheric Dynamics*

Kinematics of the atmosphere, equations of motion and their simplification.

Meteorology 332 - *Synoptic Meteorology I*

An introduction to weather map analysis.

Graduate Courses (Department of Physics)

Geophysics	521	-	<i>Plate Tectonics, Global Dynamics</i>
Geophysics	612	-	<i>Paleomagnetism</i>
Geophysics	615	-	<i>Rheology</i>
Geophysics	616	-	<i>Tectonic Theories</i>
Geophysics	618	-	<i>Heat Flow</i>
Geophysics	620	-	<i>Elastodynamics</i>
Geophysics	622	-	<i>Geomagnetism I</i>
Geophysics	623	-	<i>Time Sequence Analysis</i>
Geophysics	624	-	<i>Theoretical Seismology</i>
Geophysics	625	-	<i>The Physics of In-Situ Heavy Oil Recovery</i>
Geophysics	626	-	<i>Isotopic Studies of Stable and Radiogenic Elements</i>
Geophysics	628	-	<i>Solar-Terrestrial Relationships</i>
Geophysics	629	-	<i>Advanced Topics in Plasma and Space Physics</i>
Geophysics	632	-	<i>Geomagnetism II</i>
Geophysics	634	-	<i>Theoretical Seismology II</i>
Geophysics	636	-	<i>Mass Spectroscopy, Instrumentation Techniques</i>
Geophysics	638	-	<i>Special Topics in Solar Terrestrial Relationships II</i>
Geophysics	639	-	<i>Advanced Topics in Plasma and Space Physics</i>

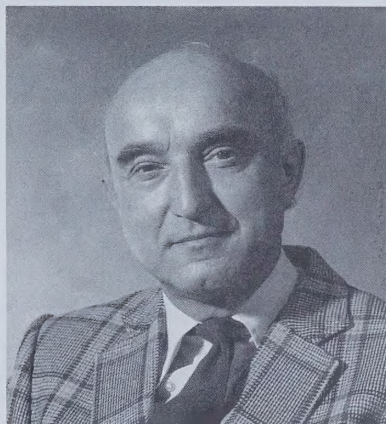
Graduate Courses (Department of Geography)

Meteorology	406	-	<i>Reading and Seminar Course in Meteorology</i>
Meteorology	425	-	<i>Atmospheric Turbulence and Diffusion</i>
Meteorology	430	-	<i>Atmospheric Physics I</i>
Meteorology	432	-	<i>Synoptic Meteorology II</i>
Meteorology	433	-	<i>Applied Meteorology</i>
Meteorology	434	-	<i>Atmospheric Modelling</i>
Meteorology	435	-	<i>Mesoscale Meteorology</i>
Meteorology	530	-	<i>Advanced Topics in Atmospheric Physics</i>
Geography	533	-	<i>Advanced Climatology</i>

6. Research Programs

6.1 Seismology, Exploration and Rock Physics

6.1.1 Seismic Waves (Franta Hron) e-mail: hron@phys.ualberta.ca



F. Hron

Theoretical and Numerical Investigations of Seismic Waves in Complex Geological Structures

*Frantisek Hron, Bao-Shan Zheng, Stephane Nechtschein, Alexander
Tsemahman, Jeremy B. Gallop, Tim Nyitrai, Hu-Shun Zhou*

In the past twelve months this group spent a considerable amount of time on the modifications of our computer software, which was originally developed for the now defunct MTS system, so that it could be executed under the UNIX operating system currently installed on both the workstations, and a new IBM parallel supercomputer SP2 that has been recently acquired by the Computing and Network Services of the University of Alberta. At the same time, we have carried out several research projects related to various theoretical problems encountered in the description of seismic waves propagating in the geological models of complicated structure.

Drs Zheng and Hron continued in their studies of the first order terms in the Ray series and their influence on the amplitude and shape of seismic wavelets recorded in the so-called near-field zone. A very good match between the synthetic traces computed according to their first order approximation of Asymptotic Ray Theory, and the synthetic seismograms produced by a highly accurate Alekseev-Mikhailenko method provided an independent verification of their theoretical work. The new theoretical formulae describing the unorthodox components of the particle motion carried by the seismic waves (oriented along the ray of *S*-waves and being perpendicular to the ray of *P*-waves) correctly describe the elliptical particle motion exhibited by the waves in the near-field zone.

A. Tsemahman and F. Hron carried out a research project dealing with the determination of elastic parameters using linear inversion of the VSP data. They showed that the determination of elastic parameters near the well of the vertical seismic profile (VSP) data was important, if sonic or density logs were not available, or when an independent confirmation of the elastic parameters obtained from logs was needed. They used a linear iterative inversion procedure

based on singular value decomposition which provided estimates of both P -wave velocity and density distributions from transit times and amplitudes of the vertical components of downgoing P -waves. The traveltimes and amplitude inversion of field VSPs was compared with the well logs. The inversion gave reasonable velocity and density profiles even when the number of observations in the upper part of the well was less than the number of unknown elastic parameters so that a layer stripping method could not be used. However, the resolution of the amplitude inversion may be improved by using a different setup with more geophones above the target zone.

The first version of software has been developed for Schlumberger of Canada. The program performs one-dimensional elastic inversion of the field multioffset, VSP data using transit times and amplitudes of transmitted P -waves. The program provided a high speed of convergence and took less than 10 min on a VAX mainframe. The performance of the program was tested using synthetic and field VSPs and well log data provided by Pan Canadian Petroleum Ltd. Estimates of the P -wave velocity from transit times of transmitted P -waves in a near-offset survey are in agreement with field well log data (Fig. 1). The agreement is good also for a far-offset experiment (Fig. 2).

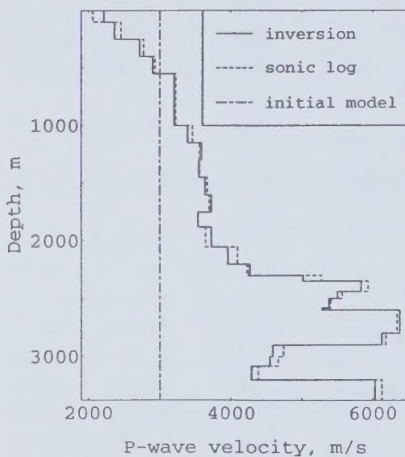


Fig.1. Transit-time inversion versus blocked sonic log. Offset 80 m, starting model 3 km/s for all layers, final residue 0.4 ms after 5 iterations.

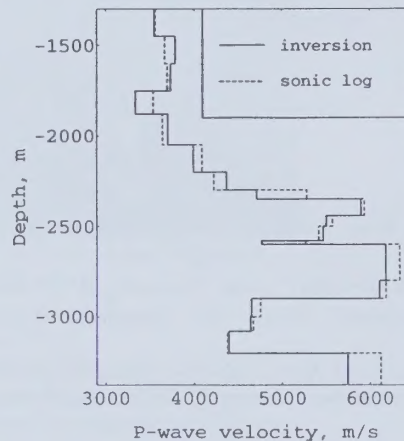


Fig.2. Transit-time inversion versus blocked sonic log for a 1600 m offset VSP survey. Final residue 0.8 ms after 3 iterations.

S. Nechtschein and F. Hron studied the influence of anelastic effects on the reflection and transmission coefficients. They used Asymptotic Ray Theory to compute reflection and transmission coefficients for two viscoelastic media separated by a plane interface. Their method differs from a standard plane wave approach, since only a local amplitude and phase matching in the vicinity of the point of incidence is required by the Asymptotic Ray Theory. In their approach, the elastic case was emulated by setting all the quality factors equal to each other. Several anelastic cases were computed by keeping the same velocities and densities while changing the Q 's. The quality factor is relatively a difficult parameter to measure exactly. Elastic coefficients are used in most synthetic seismogram computations, and quality factors are chosen from measurements or simply by estimation.

The results obtained in this study show the necessity of including the anelasticity in the calculations of the coefficients and the importance of knowing the exact values of Q . An example of results is displayed in Figure 1. The approximate Q values can lead to unrealistic amplitudes and to noticeable phase differences, as far as the coefficients are concerned.

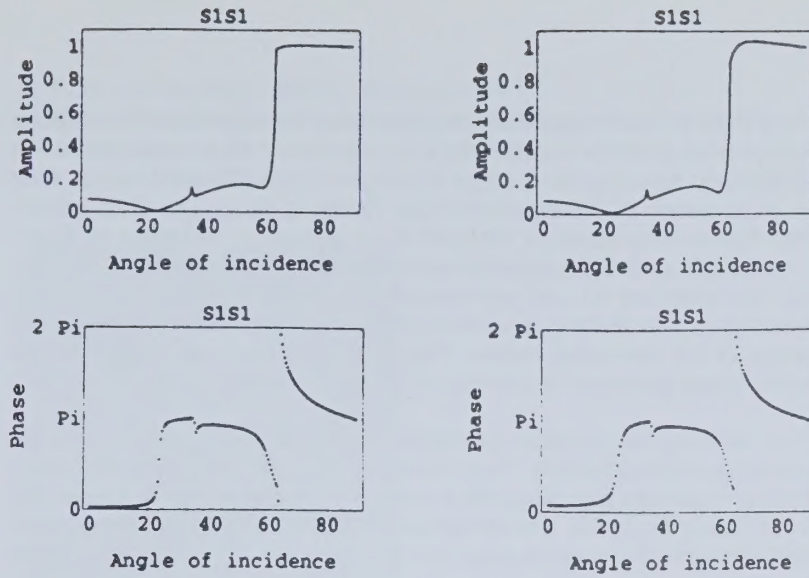


Figure 1: Example of anelastic coefficients (left: S_1S_1 coefficient computed with the right Q values, right: S_1S_1 coefficient computed with some approximate Q values).

The validity of the method which was used to include anelasticity in the Asymptotic Ray Theory has been checked by computing some seismograms and by comparing them with seismograms obtained from a finite-difference program. Figure 2 shows the primary arrival computed using both methods, for a simple 1-D model. The incident ray is post-critical and the quality factors are frequency dependent.

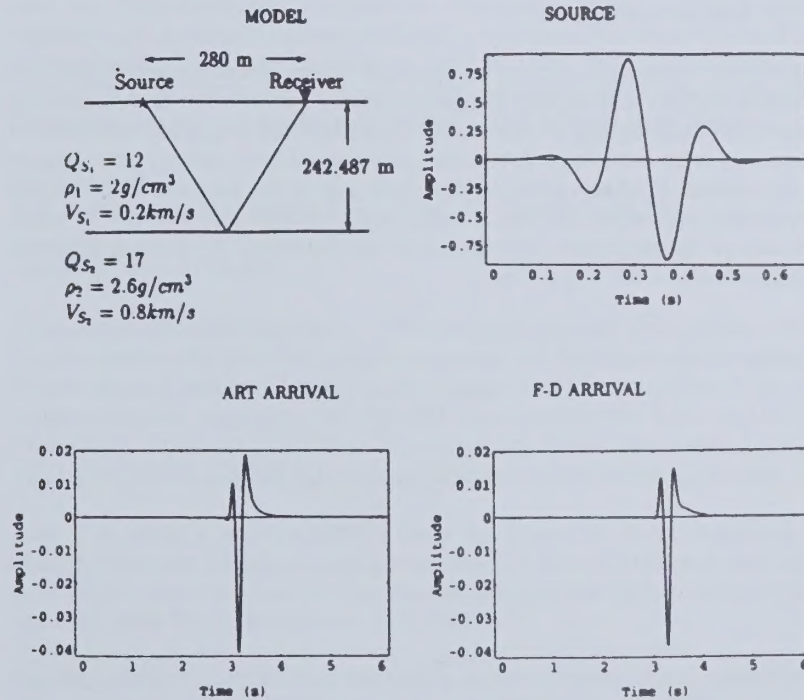


Figure 2: Top: Example of a model and a source used to compute seismograms.

Bottom: Primary arrivals computed with ART (left) and finite-difference method (right) using the above model and source.

H. Zhou, J. Gallop and F. Hron made significant progress in the development of a computer software which would provide synthetic seismic traces for a generally inhomogeneous media separated by curved interfaces featuring linear edges which give rise to diffracted waves. They used a standard zero order version of the Asymptotic Ray Theory in the regions of its validity and augmented by the higher order terms, or replaced by an alternative technique of Klem-Musatov, in areas where the zero order approximation of ART is not justified. In their computer programs the selection of the appropriate computation technique is done automatically by the computer, depending on a set of physical and mathematical parameters governing the accuracy of the computed results. Their computer package can serve as a valuable tool for any practicing geophysicist engaged in the interpretation of seismic data.

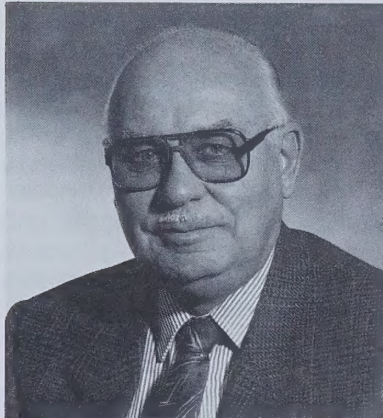
T. Nyitrai and F. Hron investigated practical applications of the reciprocity principle to the seismic data in complex geological models. Their numerical and theoretical investigations showed that under typical conditions prevailing when recording the seismic data in the seismic prospecting for oil (i.e. using explosive sources located in close proximity to the seismic boundaries) the reciprocity principle must be used with extreme care, if physically justified results are to be obtained.

Determination of Elastic Parameters Using Linear VSP Inversion

The determination of elastic parameters near the well from vertical seismic profile (VSP) data is important if sonic or density logs are not available or for an independent confirmation of estimated elastic parameters obtained from logs. We use an elastic approach to model the seismic signal propagation. The elastic case includes useful information such as head waves, mode conversions, and multiples which is treated as noise if one uses an acoustic approach. However, the ray tracing is adopted instead of numerical simulation of the full waveform to simplify modelling. The asymptotic ray theory used for computing of the signal propagation describes a variety of geological structures and can be applied to different types of data acquisition such as VSP and surface seismic.

A linear iterative inversion procedure based on singular value decomposition provided estimates of both P -wave velocity and density distributions from transit times and amplitudes of the vertical components of downgoing P -waves. The traveltime and amplitude inversion of field VSPs was compared with well logs. Inversion gave reasonable velocity and density profiles even when the number of observations in the upper part of the well was less than the number of unknown elastic parameters so that a layer stripping method could not be used. However, the resolution of the amplitude inversion may be improved by using a different setup with more geophones above the target zone.

6.1.2 Seismology (E.R. Kanasewich)
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E. R. Kanasewich,

Teleseismic Research

E.R. Kanasewich, M.J.A. Burianyk and L. Tober

We have been developing the technical basis for being able to record teleseisms (distant earthquakes) with our PDAS 100 portable digital seismographs. A secure, insulated and heated box has been developed to house the instrument and its peripherals during isolated field recording. A prototype system has been in operation for some time and has already recorded signals from distant earthquakes. As soon as other experiments permit, this system will be moved to different locations across Alberta in order to determine physical properties of the lithosphere underneath as characterized by the teleseismic wave patterns.

Lithoprobe

E.R. Kanasewich, M.J. Burianyk, G. Dubuc, J.F. Lemieux, Lei Wei

Cordilleran Transect

Two papers [Kanasewich, et al., 1994 and Burianyk and Kanasewich, 1995, in press] provide information on the physical properties across two important morphogeological regions of the Southeastern Canadian Cordillera, the Omineca and Intermontane Belts, and tie together two crustal seismic programs, SCoRE '90 and SCoRE '89, from LITHOPROBE's Southern Cordillera Transect. The data discussed in these two papers are Line 7 and 8 of LITHOPROBE's SCoRE '90 program in southeastern British Columbia.

Line 7 is along a 410 km profile from the Fraser River to Radium Hot Springs near the Rocky Mountain Trench, cutting across strike of the Intermontane and Omineca Belts. Line 8 is a 350 km north-south strike line running through the middle of the Omineca Belt, from just south of Mica Creek down to the U.S. border.

Iterative forward and inverse modelling of the seismic arrival travel-times, constrained by seismic amplitude characteristics and earlier interpretations defines a thin crust with relatively low velocities. The upper crust has an average thickness of 15.3 km and an average P wave velocity of less than 6.1 km s^{-1} with velocities at the bottom reaching $6.2 - 6.3 \text{ km s}^{-1}$. It is further characterized by velocity gradients which decrease markedly with depth, and by low velocity trends which correlate with the traces of crustal scale shear zones. A high velocity region at the west end of the Line 7 profile is coincident with a major uplift structure. The

mid-crust on both cross-sections has an average thickness of 9.2 km with velocities below 6.1 km s⁻¹ except for the extreme west end of Line 7. This defines a mid-crustal Low Velocity Zone (LVZ) in the Omineca Belt and partly in the Intermontane Belt. The lower crust, from 24 km to 36 km depth, has velocities averaging 6.6 - 6.7 km s⁻¹. Higher velocities in the deep crust may mark the westward extent of North American cratonic rocks at the Okanagan Valley. The upper mantle velocity has an average 8.0 km s⁻¹ increasing to 8.2 km s⁻¹ at the maximum depth of ray penetration at 48 km. There are indications on Line 8 that we can image layering within the mantle.

The interpreted velocity models compliment well the earlier interpretations of vertical incidence seismic reflection profiles. While there seems to be no well-defined velocity boundary between the Intermontane and Omineca belts, there are distinct velocity differences between the Intermontane and neighboring Coast Plutonic Complex to the west. The velocity structure of the crust, especially the LVZ, closely correlates with the regional isotherms.

The low velocity characteristics of the Omineca and much of the Intermontane belts may be a consequence of temperature control of the physical parameters of the crust. The lithosphere in the southeastern Canadian Cordillera is clearly anomalous with respect to much of northwest North America and in terms of crustal thickness and velocity structure, it is similar only to the Basin and Range province of the U.S.A.

Additionally, several broadside records were included in LITHPROBE's refraction and wide-angle seismic experiment in Canada's southeastern Cordillera. These fan records gave a higher level of three-dimensional coverage than that afforded simply by the grid of two-dimensional multi-shot, reversed profiles. In addition, the broadside data provided a surprising glimpse of the structure deeper in the mantle.

The broadside records, along with the two-dimensional velocity profiles of these and earlier experiments, allowed the compilation of maps of Moho structure and average crustal velocity over a large part of the Intermontane and Omineca Belts. The resulting maps show a shallow Moho in the Intermontane Belt lowering somewhat in the Omineca Belt and deepening abruptly to 50 km beneath the Rocky Mountains. Lower average crustal velocities in the Intermontane Belt are correlatable with Moho depths, as well as with the Bouguer gravity maps. There are intriguing correspondences between a Moho high, a low crustal velocity and a heat flow anomaly all centered below the Kootenay Lake area. This is a further suggestion of an enhanced source of heat from below the Moho, perhaps related to northward extensions of East Pacific Rise and Basin and Range tectonics.

A clear, unambiguous arrival seen on the furthest offset broadside records has been identified as being from below a sub-moho reflector. The kinematic characteristics of this arrival suggest that it is a wide-angle reflection from near the base of the low velocity zone, 7.8 - 8.0 km s⁻¹, leading one to conclude that the bottom of the lithosphere is at a depth of about 60 km in the southern Omineca Belt. This supports surface wave studies that conclude that the top of the asthenosphere is very shallow in the southeastern Cordillera and again is complementary with the view of enhanced heat flow from the mantle. It also shows that modern seismic wide-angle experiments at offsets in excess of 300 km can determine important properties of the upper mantle.

Alberta Basement Transect

An innovative three-dimensional reflection experiment was conducted over central Alberta (Kanasewich et al., in press, 1995) to complement the first stage of deep crustal seismic reflection profiling of LITHPROBE's Phase III Alberta Basement Transect. The seismic acquisition, undertaken in the summer of 1992, marked the beginning of multi-disciplinary probing of the crust beneath the Western Canada Sedimentary Basin to study the origin of the continent and the influence of basement structure on the sedimentary section above (Ross et al., 1995).

In planning the original two-dimensional seismic reflection experiment, the north-south, east-west grid road system of the Prairies had to be taken into account, creating at the same time problems and opportunities. The lines, numbered 1 to 10, had to be placed alternately on the north-south and east-west gravel roads, making a zig-zag line that was as close as possible to a perpendicular crossing of geologic strike. Lines 1, 3, 4, 6 and 8 were north-south while the other profiles were predominantly east-west. The three-dimensional recording was conducted in the region of the intersection of lines 2 and 3.

The perpendicular lines allowed for innovative, inexpensive acquisition of three-dimensional reflection data. This was done at what was termed '3-D corners'. Our only opportunity was at the corner created by the intersection of Lines 2 and 3. Since planning had to be long term, the location was picked more on logistical than geophysical or geological grounds.

Data acquisition was based on using, as much as possible, the existing field setup. The standard seismic reflection spread consisted of 240 receiver stations with a 50 m group interval. The source interval was 100 m (every two receiver stations) resulting in a nominal 6000% CMP coverage. The spread configuration as an asymmetric split-spread - 3150 m maximum receiver/source offset on the west/north short end and a maximum 9150 m offset on the east/south long end. The source was four 44,000 lb peak force, buggy mounted vibrators. Correlated record lengths were 18s with a 4 ms sampling rate.

The 3-d acquisition used the same line geometry, instrumentation and recording system, except that 480 channels were used in place of the standard 240. At the end of the west-east Line 2, after the two-dimensional profiling was completed, the vibrators were placed on the north-south Line 3, leaving the recording spread on Line 2. 'Broadside' shots were then recorded, creating an east-west line of CMPs. As the vibrators moved in the south-north direction, the broadside recording created additional lines of CMPs. Then by vibrating on the west-east Line 2 and recording on Line 3, after setting up the array for a new 2-dimensional grid of CMPs that could be bin stacked. With the 480 channels and only 49 extra vibrator points (for only a minimal extra cost) on each perpendicular segment (the source interval was 500 m), we achieved a 49 x 49 grid of 2000% bins (250 m x 250 m), or a 121 x 121 grid of 800% bins (100 m x 100m), in a 12 km x 12 km area.

During processing two bin sizes, 250 x 250 m and 100 x 100 m, were used. The smaller bins were considered to image reflections better, despite their smaller fold (800%), due to the smaller spatial spread - that is deep effects were less pronounced over a smaller area. Since the actual sites of VPs and recording stations are identical to the regular profiles, the same refraction derived and residual static corrections could be applied to the 3-dimensional data. A process of residual trim statics was also used to remove random static variations still in the data. Random noise attenuation, bandpass filtering and scaling, and a finite-difference migration were run after stack.

On the regular 2-dimensional Lines 2 and 3, in whose east/north intersection corner the 3-dimensional data set lies, the Moho is interpreted to be at 12 - 14 s (approximately 35 - 45 km depth), at the base of a zone of strong reflectivity. On the east side of Line 2, and the north end of Line 3, where the 3-d data volume is situated, the Moho is clearly at 14s. Between 5 - 7 s (15 - 20 km depth) there are a set of horizontal high amplitude arrivals of uncertain origin and significance. In general, the data quality is very good for Lines 2 and 3, indicating that these same reflectors might easily be visible in the corresponding 3-3 data set. However, the data quality of the profiles does deteriorate as it enters the region sampled by the 3-d experiment.

The 3-d data volume has a much lower signal-to-noise ratio than the corresponding 2-d profiles. This should not be surprising considering the difference in redundancy - 8 times for the 3-d as opposed to 60 times for the 2-d. What is rather encouraging however, is the large amount of reflectivity that is seen in the data, considering the generally poorer reflectivity in the area and the low fold. The 5 - 7 s reflective structure seen on the east end of line 2 for instance, was easily recognized and a top and bottom of the structure has been mapped. The

top of the structure has a depth differential (assuming 5000 m/s average crustal velocity) of 600 m and a northwest-southeast trend. The bottom of the structure has a 550 m variation in depth and a synformal structure. Neither trends, in present interpretations, have any correspondence with other geophysics, including aeromagnetics.

The Moho reflector was interpreted (at about 14 s) as well as a shallower deep crustal horizon (about 13 s depth). Neither of these two reflections were of the same amplitude nor were as continuous as the 5 - 7 s reflections. However, the control from picking simultaneous in-lines and cross-lines insured that a reasonable structure was interpreted. The time structure of the Moho varies from 14 to 14.5 s over the 144 square km area, and there is a tendency towards deeper Moho to the east.

During 1994, besides the Ross et al (1995) paper, another paper (Eaton et al., 1995) discussing the interactions between basement and the Phanerozoic sediment cover from the 1992 regional seismic reflection lines was published. The summer of 1994 also saw the completion of the northern portion of the Alberta Basement Transect seismic reflection program (PRAISE). The summer of 1995 will see not only the final phase of reflection profiling in southern Alberta (SALT), for which another three-dimensional experiment has been proposed, but also a regular crustal refraction/wide-angle experiment and a refraction deep probe study that will involve a profile stretching from the North West Territories, across Alberta, to New Mexico.

6.1.3 Seismology (Edo Nyland)

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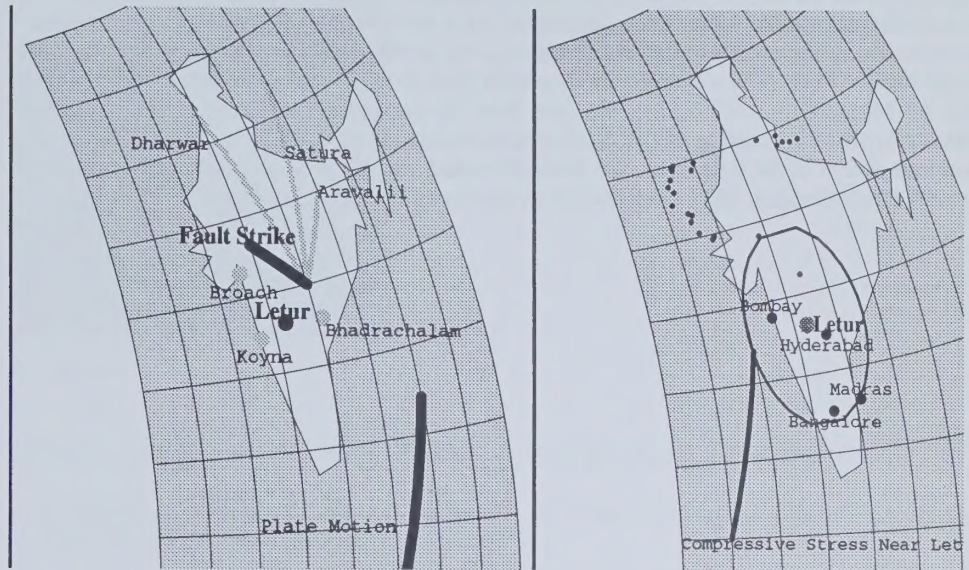
E. Nyland

Edo Nyland and colleagues continue to explore ways of controlling complicated calculations and large data sets with computer work stations. Our primary tool is Mathematica but we are integrating its use with the use of World Wide Web browsers and anonymous ftp. This allows teaching and research collaboration with a minimum of travel to common locations. Here are some examples of what is possible.

The 1993 Latur Earthquake

A collaboration with R.P. Singh in India (Singh et al., 1995, accepted for publication in *Physics of the Earth and Planetary Interiors*) explored conditions that relate to the disastrous earthquake of September 1993 in Central India and showed how disparate data from a variety of sources could be easily combined to yield new insight.

These diagrams used the cartographic data in Mathematica, archival data on tectonics and seismicity of India and automated reports on recent seismicity from the USGS.



Left... Epicenter location, location of earlier significant seismic events, fault strike from the focal mechanism, and the three major structural trends (grey lines) of the area.

Right.... Seismicity between May 1992 and March 1993, felt zone for the Latur Earthquake, some of the cities affected. The orientation of maximum compressive stress in the epicentral area.

Fort Edmonton

Particularly in this bicentennial of the founding of Edmonton exploration of the fur trade posts which were its earliest manifestation is interesting. In a collaboration with Heinz Pyszcik of the Provincial Museum of Alberta and various students in the Department of Anthropology at the University of Alberta we have used geophysical methods to investigate these sites.

Various undergraduate and high school students have mapped the gradient of the total magnetic field over much of the location occupied by the fifth version of Fort Edmonton. This site is south of the Alberta Legislature and is now covered by a park, lawn bowling green, and skating rink.

The probable distribution of archaeological remains is well understood from old maps but the magnetic field gradient over the area of the two lawn bowling greens is severely contaminated by irrigation pipes, wiring, and reinforced concrete sidewalks laid over the site after it was razed in the early twentieth century. We've had some success in eliminating this cultural noise by, among other things, fitting point source models of the ubiquitous sprinkler heads and light standards in the area. There may be useful information about the site in this residual map. In this diagram we have superimposed the magnetic gradient residuals that seem rather difficult to explain on the best archaeological data.

International Lithosphere Project

An interaction with Task Group II-4 of the International Lithosphere Project is just beginning. The principal purpose of Task Group II-4 of the International Lithosphere Project is to develop a three-dimensional data base of the physical properties of the entire earth's upper mantle (from the surface of the earth to a depth of about 800 km). This data is to be in a form that is easily accessible to imaging programs. As a pilot project the task group prepared a representation of the structure under the southern tip of the Kamchatka peninsula. This is the way the Pacific Plate subducts under the Eurasian plate in this area. It was generated relatively easily by Mathematica. Checking the data base is most easily done graphically and the animation typified by cutting of the display at decreasing depth is very useful for identifying anomalous points in the data base. We have generated animation sequences up to 15 seconds long with this technique. They demonstrate anomalous parts of the data very vividly.

6.1.4 Mineral, Rock and Borehole Physics (Doug Schmitt)
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D. Schmitt

Mineral, Rock and Borehole Physics - Petrophysical Laboratory

D.R. Schmitt, A. Kebaili, Y.Y. Li, J.B. Molyneux, Y. Wang, C. Hickey, J. Haverstock, B. Madu, L. Tober, M. Mah, P. Bashran, J. Viau, E. Springer

Introduction

Research focuses on rock and mineral physics especially as these affect the physical properties controlling seismic wave propagation and the conditions affecting crustal stress and quantitative stress measurements. Towards these ends the Petrophysical Laboratory is conducting a broad based research program consisting of both laboratory physical property measurements and field wellbore seismic and logging studies.

Ultrasonic Borehole Televiewer Logging

The ultrasonic borehole televiewer is an open wellbore logging tool which creates an image of wellbore wall rock using ultrasonic principals similar to those applied in medical imaging. The system operates by sending out an ultrasonic pulse which is reflected from the wellbore wall back to the logging tool where it is detected. The ultrasonic transducer inboard the instrument rotates around the tool axis 3 times per second while pulsing at a rate near 2000 Hz. An image is created by mapping either the travel time or the amplitude of the reflected pulse with respect to depth and magnetic north. An example of recently acquired data in a highly fractured formation near Revelstoke, British Columbia is shown in Figure 1. The amplitude image is most useful for locating fractures and veins. The travel-time image provides a measure of the wellbore cross-section shape from which stress related breakouts may be seen.

We have previously described a new hardware system constructed at the University of Alberta for digitally acquiring both the travel-times and the amplitudes of these pulses. In addition to being used in our laboratory, the system is being employed at Stanford University and also as part of a large project to log many of the deep wellbores (> 5 km) in the former Soviet Union based out of the Geo Forschungs Zentrum, Potsdam and including the stress measurement groups at the Geophysikalisches Institut der Universität Karlsruhe, Stanford University, and within NEDRA, the agency overseeing drilling in Russia. Preliminary results from logging at two sites were reported on at the International Symposium on Continental Drilling held in Santa Fe this last April.

In conjunction with a number of wellbore seismic measurements discussed above, televiewer logging of wellbores near Matagami, Quebec and Sudbury, Ontario was carried out. We are presently analyzing these data for stress orientations as breakouts were seen in the deep Matagami wellbore near 800 m. The Sudbury logging is also of interest as the complementary seismic experiments in this wellbore were contaminated with tube waves which appear to be generated by fluid filled open fractures at depth. In 1995 we anticipate further televiewer logging in Ontario and Saskatchewan. A recently drilled speculative wildcat well in the Canadian Shield in Northern Alberta may also be logged if funding can be acquired.

Seismic Anisotropy

Seismic anisotropy within sedimentary basins is often discussed but seldom quantitatively measured. This anisotropy arises from a number of sources ranging from intrinsic anisotropy of the material itself to averaging effects due to layering which is thin relative to the predominant seismic wavelengths. From a practical perspective, this anisotropy is important in that the precision of seismic images are greatly improved upon if it is included and because anisotropy itself may be an indicator of certain types of formations such as hydrocarbon source shales. We had earlier discussed a new approximate approach to determining the variation of seismic velocity within the vertical plane in a given depth interval by a slant stack (or τ - p analysis) from a multi-offset and depth VSP experiment.

This approximate method was applied by graduate student Mr. Ahmed Kebaili to a special VSP data set acquired by us at a site in the Oil Sands near Fort McMurray, Alberta. Presently, the theoretical basis of the technique has been further investigated and these studies have shown that the method may be further modified to measure the anisotropy of the formation between any two receivers at depth in the wellbore without having to conduct time consuming and error generating layer stripping of all overlying layers. The method essentially exploits the shape of the locus of the direct arrivals in the τ - p domain to determine how the velocity varies with angle of incidence. The great advantage of this approach is that the data at the angle of incidence is easily determined as it is implicit within the horizontal slowness p . An application of the method is shown in Figure 2 where the velocity as a function of horizontal slowness (and indirectly angle of incidence) over the interval between 75 and 125 m depth is graphed. This interval corresponds to a finely layered sequence of fast sands and slow shales and as such is expected to appear to be anisotropic. However, the observed anisotropy is greater than could be expected theoretically from a stack of layers composed of isotropic materials. This suggests that the layers are themselves intrinsically anisotropic. This is not that surprising as shales are known to be highly anisotropic. We are presently conducting laboratory ultrasonic measurements on shales taken from cores at this site in order to better characterize this intrinsic anisotropy.

Finally, the slant stack method is now finding application in the characterization of anisotropy in the laboratory and is being extended to industrial materials. Because of their construction geometry, many composite materials are inherently anisotropic and determining the anisotropy can provide some measure of the material's quality. In these laboratory tests, a large number of small ultrasonic transducers (1 mm diameter) are attached along a line to the surface of a block of the material. Considerable technical efforts were expended to make these transducers as broadband as possible (i.e. to produce as sharp a pulse as possible) and techniques to bond and damp the transducers were developed. Whereas the undamped transducers had nearly all of their energy at 750 KHz, the damping allowed for a nearly flat response from 300 KHz to 2 MHz and provided a reasonably sharp waveform which allows for better analysis. A series of waveforms acquired from a sample with orthorhombic symmetry are shown in Figure 3. These data were analyzed to extract the velocity variations within the plane containing the sources and receivers which is shown in Figure 4.

Vertical Seismic Profiling

In the last year we conducted two field trips in February and June to Eastern Canada to carry out wellbore VSP measurements for purposes of mine delineation in collaboration with the Geologic

al Survey of Canada. Economic ore bodies in Canada are located at increasing depth and as a result conventional conservative exploration techniques which consist primarily of grid drilling over electrical anomalies are becoming prohibitively expensive. Furthermore, electrical techniques cannot distinguish between the desired massive sulphides and similarly conductive disseminated sulphides and graphite. Consequently, these experiments were conducted to test whether or not seismic techniques could provide a complementary measurement of the subsurface properties for location of massive sulphides ore bodies.

Experiments were conducted to the maximum depth available with our wireline system to 1168 m in one wellbore. The acquisition system consists of a seven conductor wireline, a downhole three component geophone, and a BISON 12 channel recording system coupled to an older IBM laptop computer. VSP's were acquired at seven different sites near Matagami, Quebec, and Timmins and Sudbury, Ontario. At one site a pseudo 3D VSP experiment with numerous surface source positions and multiple depths was carried out. Preliminary results obtained appear to indicate that the seismic methods show promise both for delineating the geologic structure along the shear zones where the sulphides are often encountered and for the direct detection of the sulphides as a result of the strong physical property contrasts with the surrounding ground rock. In the coming year we will be analyzing the data obtained for shear waves and for anisotropy whilst scientists at the GSC concentrate on methods of imaging and it is anticipated that these data will be approved for release in 1995. We expect to conduct further of these measurements in 1995 to greater depths. We also hope to acquire a newer and higher resolution data acquisition system together with a field deployable SUN computer to allow in field data quality checks as it was often found that the data acquired in these mine settings was highly contaminated with electrical noise.

Further, Mr. Yanqun Wang has completed the bulk of his M.Sc. research in the area of seismic tomography. His project focused on reconstructing the seismic velocity structure from a surface to wellbore seismic experiment. This is a particularly difficult problem in that the limited range of angles through which the seismic energy may pass limits the ability of the imaging technique to resolve the structure. Mr. Wang has developed an iterative tomographic technique which employs a forward modelling of the expected travel-times through the geology. This forward modelling procedure has the advantages that it calculates the travel-times to all points within a velocity structure grid specified by the researcher and may easily account for travel time variations due to compressional to shear wave arrivals. This technique is straightforward being based solely on Huygen's and Fermat's principals and as a result complex geological models are rapidly calculated. A great advantage of this method is that critically refracted rays are automatically accounted for. A disadvantage, however, is that the method only allows for the calculation of the first arriving ray. Mr. Wang has further developed the model to include reflected and diffracted seismic energy. Using both direct and reflected waves, Mr. Wang conducted a satisfactory tomographic modelling of an anomalous velocity anomaly (a steam zone in the oil sands). This model had excellent horizontal resolution but was somewhat in error in the vertical dimension due to the fact that the rays used in the tomography were mostly vertically propagating. We are presently picking travel-times from a multi-offset, multi-depth VSP experiment carried out by us near Fort McMurray, Alberta in order to test the tomographic routine on real data.

Rock Velocities

P-wave velocity measurements are carried out by graduate student Mr. Joseph Molyneux on rock sampled from surface exposures of a Proterozoic shear zone associated with a strong seismic reflector observed in a recently acquired reflection profile in the Canadian Shield near Flin Flon, Manitoba. The shear zone dissects a complex assemblage of mid-amphibolite grade metasedimentary and metavolcanic rocks lying between less deformed granodiorite plutons. P-

wave velocities (measured at 200 MPa of confining pressure) vary from 5.68 km/s to 6.28 km/s perpendicular to the plane of foliation and from 6.09 km/s to 6.98 km/s parallel to the plane of foliation, and velocity anisotropy varies from nearly zero to 21.4%. The anisotropy does not vary systematically across the exposed shear zone (Figure 5a). When densities are considered, the elastic impedances calculated using both the mean and the foliation normal velocities (which are most representative of the velocities sensed in the reflection profile) both show considerable variation along the profile and suggest that the observed seismic reflections are produced by impedance changes both within and at the boundaries of the deformed metasedimentary band (Figure 5b). Average amplitude reflection coefficients of 0.030 and 0.033 are calculated for the mean and the foliation normal impedances, respectively. This taken together with the agreement between the observed mean velocities and those predicted on the basis of mineral modes, suggests that the reflectivity of this zone is primarily due to compositional variations which are enhanced only slightly by strain induced velocity anisotropy.

Some secondary observations from this study were that the anisotropy correlated negatively, positively, and not at all with the volume percent of plagioclase, amphibole, and quartz, respectively. The lack of correlation of quartz with the strain induced velocity anisotropy is somewhat surprising as it is often assumed that seismic anisotropy in the deep crust is controlled by the alignment of quartz crystals.

In the upcoming year, we will be continuing these velocity measurements along the same Annabel Lake Shear Zone but at a point where the rocks are of a greenschist metamorphic grade. This second crossing point is also associated with strong seismic reflections and here will be referred to as the Nesootao Lake Reflector. As a result, the scientific rationale for these measurements are to examine the effects of changing metamorphic grade on the causes of reflectivity. Specific questions to be addressed are 1) will any pattern in strain induced anisotropy emerge in the greenschist facies shear zone, 2) will anisotropy be an important factor in the overall reflectivity of this zone, and 3) what minerals will predominantly control anisotropy in these samples.

In our earlier work, transit times were determined by direct measurement on the digital oscilloscope. We have further refined our system since that time to allow automatic acquisition of the waveforms and control of the pressure vessel system. That is, the system can now cycle up and down in pressure to 200 MPa in steps as low as 1 MPa and also obtain a given ultrasonic waveform from the oscilloscope (Tectronics 4500) onto the controlling computer (Mac Quadra 650) at each pressure step. The new system will acquire up to 100 waveforms or more from which the transit times may be determined using well known seismic analysis methods. We have also developed new methods of transducer damping which introduce a sharper (broadband) pulse to the sample which improves the ability to measure travel-times accurately. It must further be noted that Mr. Brian Madu has set up an excellent machine shop dedicated solely to the preparation of rock samples for laboratory experiments. This machine shop presently includes two rock saws, a drill press modified for coring operations, a lathe, and a modified surface grinder. Accessory equipment includes a new vacuum drying system and an accurate digital balance. We hope to be able to obtain an optical petrographic microscope sometime soon.

Seismic Monitoring

The large majority of the heavy oil sand deposits in the Western Canadian Sedimentary Basin must be exploited using wellbore methods the most preferable being the injection of steam which heats the oils allowing them to flow more freely. Often in these projects there is the risk that a given process might not fully exploit a reservoir if, for example, steam had not migrated to all sections. Consequently, there is a need to monitor the progress of the steaming process with time in order to optimize the recovery.

A number of 3D reflection surveys have had great success in showing how the reservoir has generally changed as a result of physical property variations produced by pore pressures, gas

saturations, oil content, and stress in a steamed reservoir with time. Despite this success, full 3D seismic surveys have the disadvantages that they require a number of days to complete, they are expensive (>\$500,000), and substantial processing time is required.

We are presently involved in a series of seismic experiments near Ft. McMurray and in a collaborative effort with ESSO Research at Cold Lake towards the development of a less expensive and more rapid monitoring technique. Here, the evolution of a single seismic trace between a set seismic source and receiver position is monitored with time. Changes in the observed seismic waveforms (e.g. waveform character, frequency content, reflectivity, time shifts) are diagnostic of changes in the reservoir and may be mapped. The advantages are 1) fewer shot-receiver combinations are required (≈ 200), 2) data will only require a limited amount of processing, and 3) the entire experiment is conducted over short time periods (hours?) allowing nearly real time application of the method.

We have already had some limited success with this approach, data acquired at the ESSO Cold Lake facility by us show that although little change is seen in the waveforms representing energy reflected from formations above the disturbed oil sands, reflections within and below this zone show considerable variation over the period of the 2 month trial (Figure 6). These traces were obtained on a 24 channel seismic data acquisition unit temporarily loaned to us by Exxon Production Research. It must be noted that to make each trace required stacking 25 shots of our surface Betsy gun seismic source. Unfortunately, the frequency content of the Betsy gun signal is poor (<50 Hz) and as a result we will be experimenting in future with higher frequency sources.

Dr. C. Hickey worked with us on attempting to develop ways to quantitatively characterize the changes in the seismic waveforms. A cross-correlation scheme was first employed but this had the disadvantage that it tended to average out any signal. We are presently attempting to use much more direct approaches such as monitoring the change in the travel-time to the lower, but strong, seismic reflection from the Paleozoic carbonates which lie below the heavy oil reservoir at Cold Lake. This latter work was assisted by undergraduates Mr. James Viau and Mr. Marko Mah and research assistant Mr. Jay Haverstock. We expect this work to increase in 1995 with the addition of two new SUN SPARC5 computers to the petrophysical laboratory both running MATLAB and a new locally constructed IBM486DX2-66 machine which runs the VISTA seismic processing package.

Rock core and wellbore wall damage: Implications for wellbore logging and stress determination

In situ stresses are concentrated by the wellbore cavity and are considered important in producing wellbore breakouts which are a spalling of the wellbore at preferential azimuths with respect to the stress field. The azimuths of these breakouts yield the principal stress orientations and have provided information on stress states from many locales. However, before simple "infinite cylindrical cavity" stress concentration solutions apply to breakout formation, the wellbore wall rock and core have already been subject to a more complex state of stress concentration generated by the bottom hole geometry. These bottom hole stress concentrations have not been fully studied but since they are known to damage cores and likely the near wellbore wall rock a better understanding of these stresses will have significance towards i) the interpretation of geophysical logs and laboratory core measurements; ii) the description of wellbore breakouts some of which may be initiated at the wellbore bottom, and perhaps most importantly iii) a potential new method of constraining stress magnitudes by examining the degree of damage produced in the core samples.

In regards to the last point, it has long been known that many cores contain uniformly spaced saddle shaped fractures which if sufficiently severe, results in individual saddle shaped 'discs' (i.e., 'Pringles' potato chips). The spacing of these discs appears related to the stress magnitudes; higher stresses equate to thinner discs. Further, the disc amplitude (difference in height between the peak and the trough of a disc) may be related to the difference in the two principal stress magnitudes. Jaeger and Cook indicated on the basis of an elastic solution that

tensile stresses generated at the base of the core were responsible and this was confirmed by Dyke in a two dimensional finite element analysis.

These studies demonstrated that the bottom hole geometry is important but left unresolved a number of questions including: i) What is the relationship between the disc thickness and the stress magnitudes? ii) How is the amplitude of the saddle shaped fracture influenced by the principal stresses? iii) At what point do macroscopic core fractures, visible to the naked eye, form? iv) How will cores retrieved from horizontal wellbores (now extremely popular for hydrocarbon extraction) be damaged? And finally, v) Can these core fractures or the microscopic damage leading up to them provide an indication of in situ stress magnitudes?

We have already conducted preliminary studies towards resolution of these issues. Differential strain measurements are underway on core samples obtained from the Alberta basement in order to determine whether cores which do not display any macroscopic discing cracks might otherwise contain substantial microcrack damage. We have set up a completely automated control and data acquisition system precise differential strain measurements up to 200 MPa over time periods to date as long as 52 hours allowing the acquisition of substantially more data than possible manually. In a measurement on a core from a depth of 4700 m in the Alberta foothills (courtesy of Shell Canada Research) the major microcrack families were not aligned with the principal stress directions and suggests that the core microcrack damage results from the coring operations and not from stress relief which would be expected to produce large crack strains parallel to the directions of the principal stresses. Graduate student Mr. Li has also begun preliminary 3D finite element modelling to determine the stress concentrations in a vertical core still attached to the groundmass which is subject to an uniaxial stress. The preliminary results indicate that the length of the core controls the magnitude of the greatest tensile stress; hence, a core must reach a critical length before the macroscopic discing fracture can be produced; these results show much promise towards more fully describing the uniformity of the core fractures. We are in the process of mapping the observed fractures seen in cores from the Alberta Basement in existing depositories and in cores from Sudbury provided by INCO. We hope to be able to use the morphology of these fractures to provide an indication of the stress states within these different geologic areas.

Quantitative stress measurement using optical interferometry

A problem with many quantitative stress measurement techniques from wellbores is that in the analysis of the data it is almost always assumed that the wellbore is parallel to a principal stress. While this might be true in vertical wellbores it cannot be the general case in deviated or horizontal wellbores and there is a need for new methods. We are working on an optically based technique which shows promise towards this goal, the method employs optical interferometry to record micron scale stress relief displacements induced by the drilling of a small hole into the side wall of a wellbore. This method has found wide usage in the mechanical engineering community with strain gages; and there are parallel developments to ours at Stanford University and at the Taiwan National University. There are a number of advantages of this technique in that each individual measurement is rapid allowing many measurements to be made, and that the technique will allow calculation of the complete stress tensor (all six components). Such measurements will have special significance towards stress measurements in civil and mining engineering, and also has a longer term potential for monitoring of changes of stress states near possible earthquake faults.

The raw data consists of dark interferometric fringes superimposed on the holographic image of the surface of the wellbore. The magnitudes and directions of these displacements are dependent on the state of stress at the wellbore wall, conversely, measuring these displacements allows one to determine the stress given an appropriate relationship between the displacements and stress. This relationship is complex and recently we have conducted an extensive series of laboratory stress relief experiments under controlled conditions to test the validity of a finite element displacement model. Experiments in plexiglas showed good agreement with the finite element displacements.

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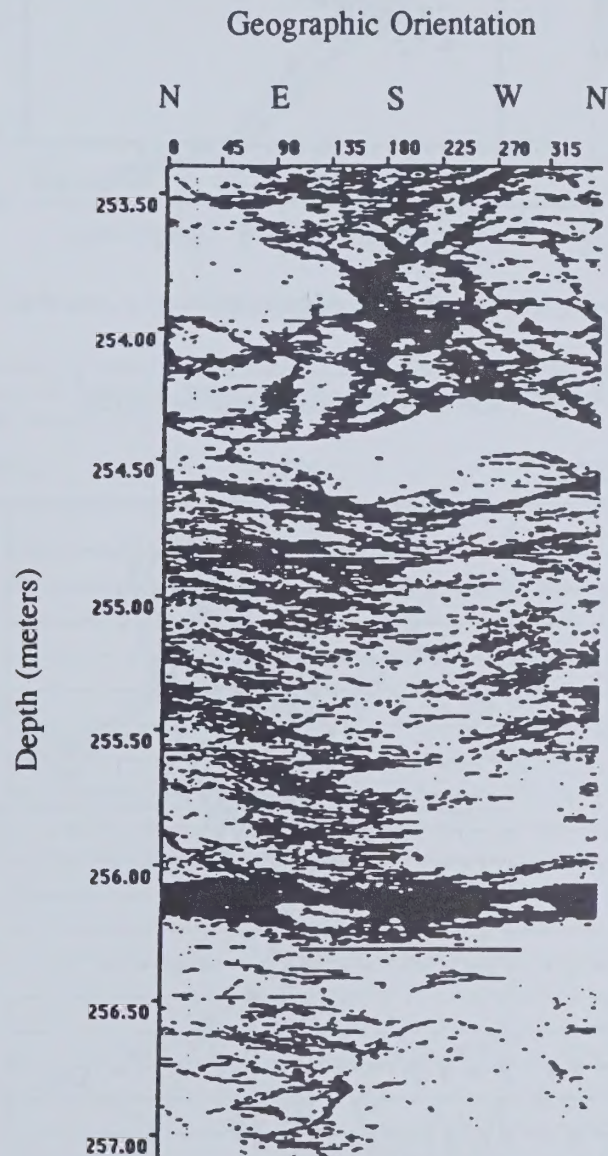


Figure 1. Ultrasonic televiewer travel-time images from a highly fractured metamorphic formation. Fractures appear as sinusoids in the image which is corrected to be oriented with respect to geographic north along the left and right hand sides of the image.

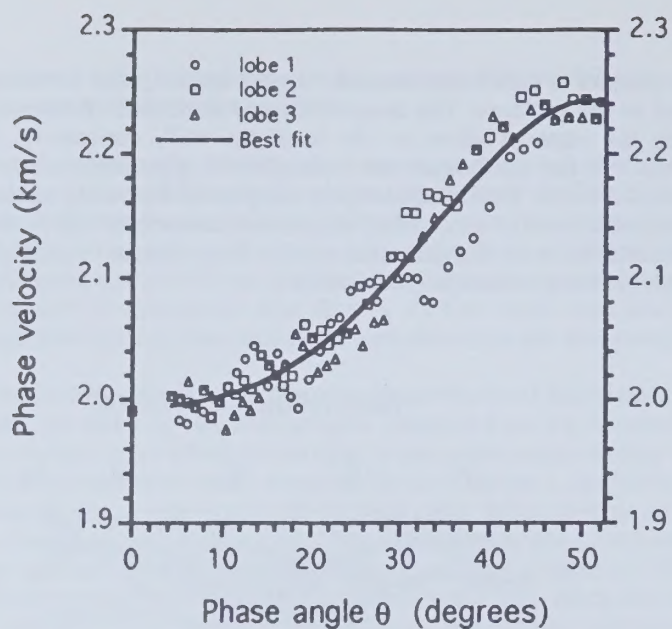


Figure 2. Variation of velocity with angle of incidence through a sand-shale sequence between 75 m and 125 m depth.

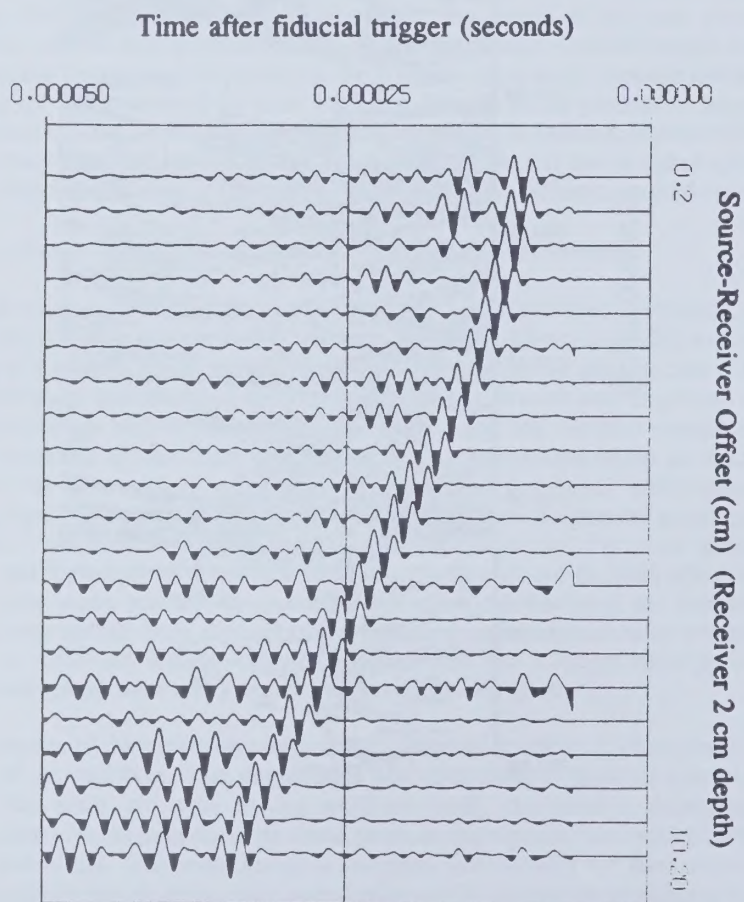


Figure 3. Broadband ultrasonic waveforms obtained from miniature transducers developed in our laboratory.

Phenolic: λ - λ plane

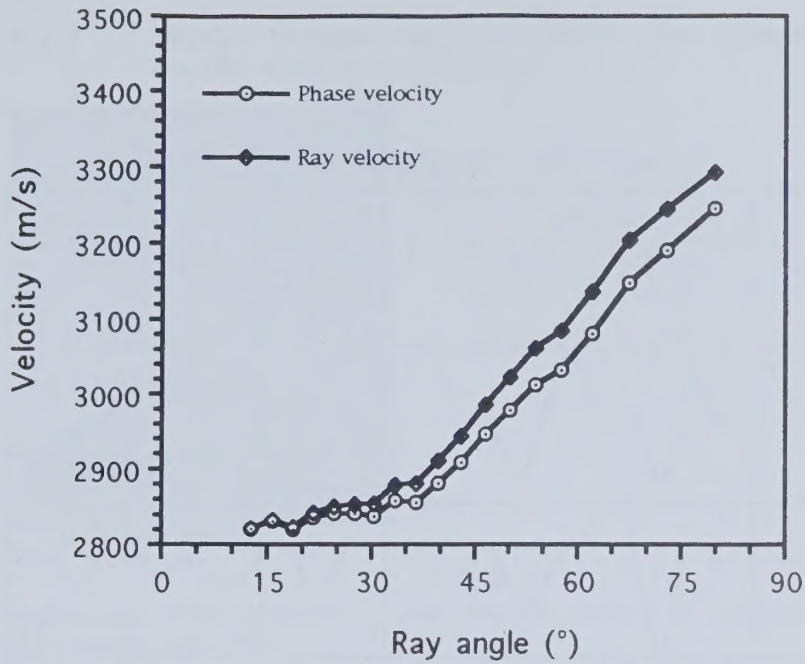


Figure 4. Variation of velocity with angle of incidence as determined from the slant stack analysis of the data of Figure 3. Material is an epoxy phenolic composite with orthorhombic symmetry. Material courtesy of Dr. J. Brown.

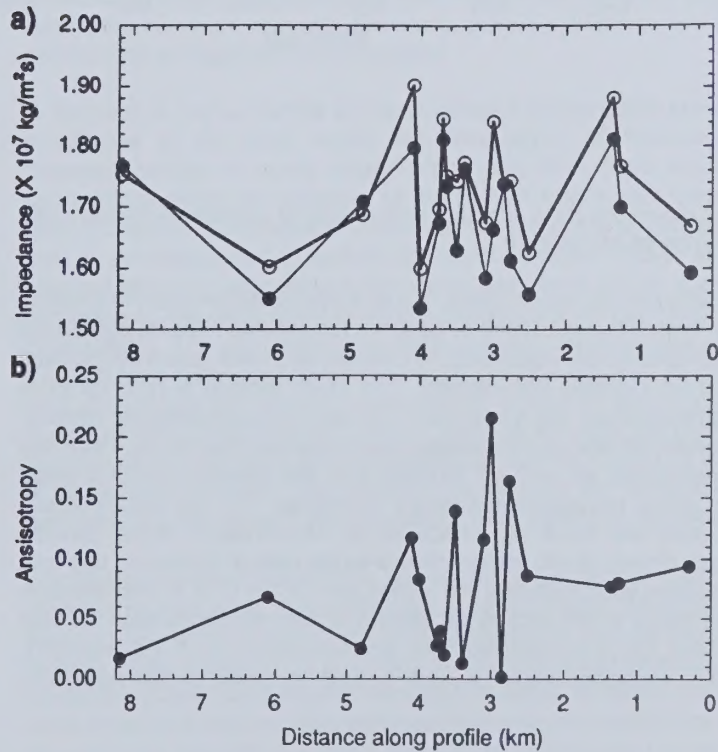


Figure 5. a) Acoustic impedance versus surface position along the seismic profile, Open circles represent impedances determined from the velocities measured perpendicular to foliation and filled circles represent impedances determined from the mean of the measured velocities, b) Anisotropy measured in the laboratory versus surface position along the seismic profile.

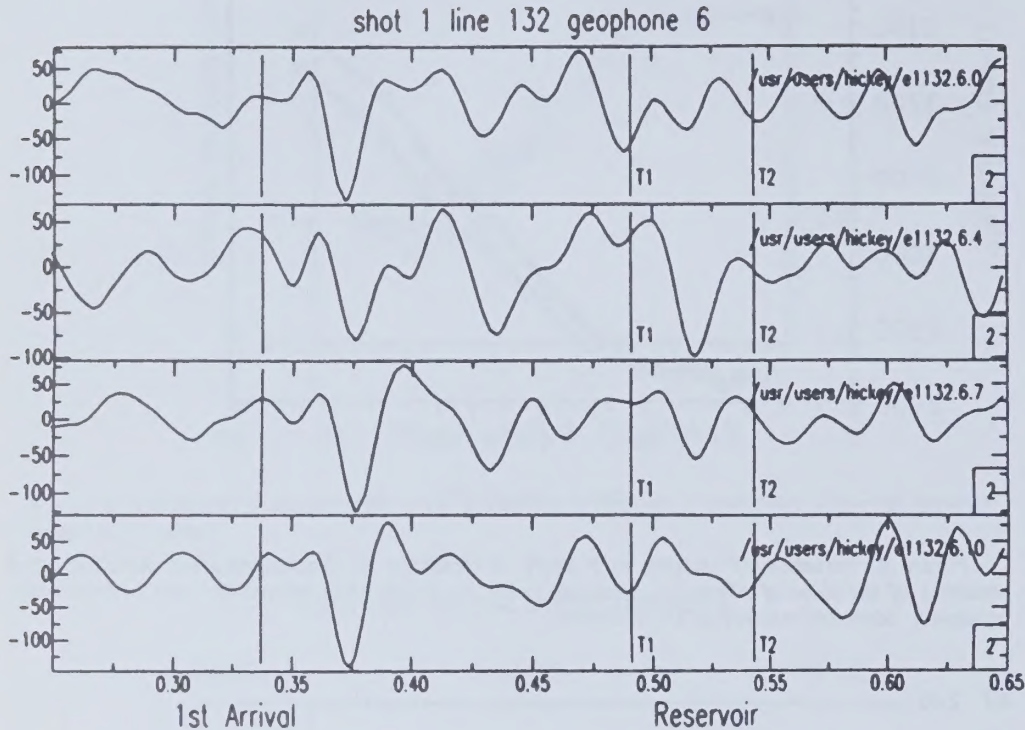
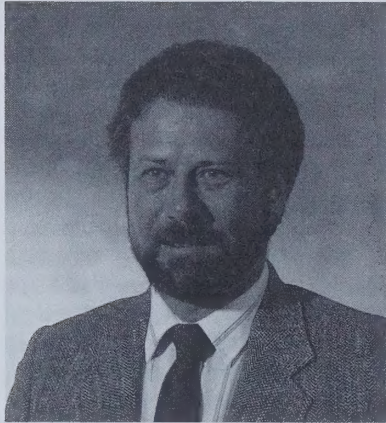


Figure 6. Observed seismic waveforms for a constant source-receiver position at various times during 2 months of production from an oil reservoir.

On-going research at present includes the development of a new electronic method of recording the displacement fields using video images instead of film, we received an NSERC equipment grant in the last year to obtain appropriate equipment to conduct this work and were assisted by undergraduate Mr. Parminder Bashran this summer. The video method is referred to as Electronic Speckle Pattern Interferometry and it essentially operates by comparing the 'speckle' patterns (i.e. the grainy appearance of objects illuminated under coherent laser light). Once this system is sufficiently well developed we will go forward with the construction of a small borehole system to conduct stress measurements in dry wellbores. We are also working collaboratively with Drs. Ahrens and Stock at Caltech on the improvement of the Caltech stressmeter. My laboratory has already made improvements to the optical system of this tool and we will be carrying out further improvements and testing here at the U of A over the next year in anticipation of deployment of the tool in an already drilled wellbore near the San Andreas fault close to Palmdale, Ca. We have also been approached by Dr. F. Cornet (IPG, Paris) regarding the possible implementation of such optical methods in his hydraulic fracturing system.

6.1.5 Physical Processes in Porous Media (Tim Spanos)
e-mail: tim@phys.ualberta.ca



T.J.T. Spanos

Macroscale thermomechanics and thermodynamics of multiphase media

T.J.T. Spanos, Dave Yang

Some of the applications of this research include fluid flow and mechanical deformations which occur during geophysical processes in the earth, the thermodynamic behaviour of macromolecular systems and the flow of suspensions. Geophysical applications of this work include transport of ground water, seismic studies of the earth's crust including such practical applications as oil and gas exploration, monitoring enhanced oil recovery, understanding and simulating heavy oil recovery processes, porosity diffusion associated with reservoir loading and the remote triggering of earthquakes.

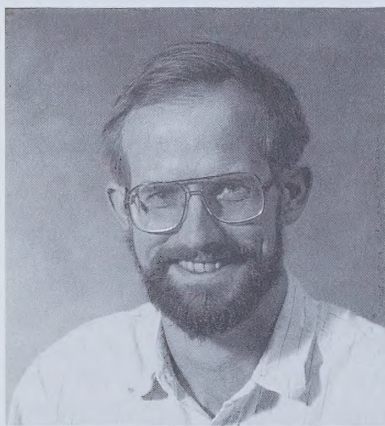
In the case of porous media we have started with the basic physical equations and boundary conditions at the pore scale, the description of mechanical deformations and the thermodynamics at much larger scales has then been constructed subject to specific assumptions about the structure of the porous matrix and specific physical processes. The flow of miscible and immiscible fluids in homogeneous porous media have been considered as well as generalizations to include the effect of phase change and heterogeneities. All of the required physical parameters in this theory have been clearly specified in terms of the physical properties of the component materials and straight forward macroscopic (process dependent) experiments. The equations describing seismic deformations of an inhomogeneous porous medium have been constructed by incorporating a porosity gradient into this theory. Here we have shown that the resulting macroscopic equations are entirely different in form than the equations for a homogeneous porous medium and that the form of the equations of motion depends on the nature of the heterogeneities; not just values of the macroscopic parameters as is commonly assumed. The boundary conditions for fluid filled porous media have been derived in a form which is independent of one's choice of equations of motion.

Equilibrium thermodynamics for porous media has been considered with special emphasis on its basis in pore scale thermodynamics. Macroscopic thermodynamics for porous media is found to be a set of relations in terms of quantities that are meaningful at the macroscale. Its validity rests, however on accepted thermodynamical principles on the pore scale. In this analysis we have used volume averaged relations to derive macroscopic consequences or to serve as a check and we have restricted this study to equilibrium thermodynamics. We are led to accord the porosity variable a role on the same footing as the mass density and the strain tensor. Examination of Biot's (1956) use of an "elastic energy potential" which forms the foundation of his theory of poroelasticity (and subsequent generalizations of it), suggests that some physical inconsistencies are inherent in that theory (i.e. it has been shown that the Biot theory is not a physical theory).

Extensions of current volume averaging theorems are being investigated. These new procedures are required to obtain macroscale descriptions of chemical reactions, diffusion phenomena macromolecular dynamics, etc.

We have developed a probabilistic cellular automaton model which simulates hydrodynamic flow behavior. The model is constructed on the premise that by introducing floating-point speed and trajectory, one can relax the isometric-constraint due to isotropy imposed on the lattice of the strictly discrete lattice gas models. The purpose of the lattice is to discretize space, and to allow for site-to-site propagation of particles. By associating the speed of the particle with the probability of a translation during the propagation phase, one can allow for multiple site-to-site transition. This together with the non-deterministic collision rule modeled on local conservation of particle number, momentum, and energy constitute the evolution phase of the model. We demonstrate that the evolution rule inherently promotes the appearance of a stationary particle speed-distribution which can be used as an empirical definition of "temperature" for the system. The low velocity flow described by the model in simple geometry is identical to the prediction of the incompressible Navier-Stokes equation, and allows for the determination of transport coefficients for momentum transfer. The probabilistic nature of the model allows for straightforward generalizations to problems of multiphase flow in heterogeneous porous media.

6.1.6 Experimental Petrology (Bob Luth)



Bob Luth

A number of independent research projects are underway in this laboratory. Most of these projects capitalize on the capabilities for precise high-pressure (to 27 GPa), high-temperature experimentation on mm³-sized samples available in the multiple-anvil Superpress.

Projects by internal users:

Study of phase relations and mineral chemistry in eclogite and carbonated eclogite to determine the fate of the basalt portion of subducted lithosphere (D. Hauth, R. Luth)

Subducted lithosphere consists in part of altered basaltic oceanic crust. At high pressures, this crust will transform into eclogite, a garnet + clinopyroxene-bearing rock similar to some xenoliths sampled by kimberlites. A single study prior to this one provides the only constraints on the phase relations of eclogite at pressures > 5 GPa. There are no data available for eclogite + CO₂ systems at > 5 GPa. This study, which forms part of D. Hauth's PhD research, is directed at providing information on the phase relations and mineral chemistry of

eclogite assemblages, both volatile-free and carbonated. Particular attention is being paid to the subsolidus phase relations and the composition of carbonates present, with the idea of determining the reactions that control the stability of carbonate, relative to CO₂, in eclogites. Identifying these reactions is of interest to contrast to the analogous reactions in peridotites, which involve olivine, a phase that is not present in eclogites.

Density of silicate melts at high pressure

(R. Knoche, R. Luth)

The density of melts at high pressure may be determined by using the sink/float method, wherein mineral spheres of known density are used as buoyancy markers, which sink or float in the melt depending on the relative densities of the markers and the melt. This method has been successfully employed (e.g. Agee and Walker, EPSL 114, 315, 1993) to determine densities of melts in both piston-cylinder and multi-anvil apparatus. To understand magmatic processes in general, however, a much broader database of densities of silicate melts at high pressure and temperature is required.

To apply this technique successfully, several requirements must be met:

- (1) The temperature- and pressure-dependent density of the marker material must be known, preferably from direct measurements.
- (2) The markers and the melt should not react on the timescale of the experiment, because reaction will change the densities of the phases.
- (3) The density of the marker must be close to the density of the melt in the P, T range of interest. Ideally, there should be a density "cross-over" in this P, T range.

To expand our database of the density of melts at high pressure, we have studied sodium silicate and albite melts, using spinel, forsterite, and adularia marker spheres. Some of the problems outlined above were overcome in part, which allow constraints to be placed on the densities of these melts. Serious difficulties remain, however, especially in requirements (2) and (3) above. Therefore, the sink/float technique has significant limitations in efforts to determine the density of silicate melts at high P and T except in rare, favorable circumstances, despite its elegance.

Decarbonation reactions involving garnet

(R. Knoche, R. Luth)

Carbonates are significant potential hosts for primordial and subducted carbon in the Earth's mantle. If the carbonate coexists with silicates and reduced carbon (diamond or graphite), useful insights into the oxidation state of the mantle may be obtained from various carbon-carbonate-silicate equilibria. Carbonate-silicate-vapor reactions have been studied to constrain the possible reactions by which carbonate + silicate assemblages may form from carbon-bearing vapor + silicate assemblages with increasing pressure. In peridotitic (olivine-bearing) rocks such as lherzolite, which is thought to be the major rock type in the mantle, the carbonate-forming reactions invariably involve olivine.

In eclogitic rocks, such as subducted, metamorphosed MORB, the essential mineral assemblage is omphacitic clinopyroxene + garnet, without olivine. For these mantle rocks, alternative carbonate-forming reactions must be sought. Luth (in press, Contrib Mineral Petrol) proposed that the reaction $\text{Dol} + \text{Cs} = \text{Di} + \text{CO}_2$ (1) (Cs = Coesite, others as above) is a candidate for carbonating eclogites, and determined the location of this reaction between 4 and 6 GPa. Another possibility is that garnet reacts with CO₂ to form carbonate. One model reaction for this could be $3 \text{Mc} + \text{Ky} + 2 \text{Cs} = \text{Py} + 3 \text{CO}_2$ (2) (Ky = Kyanite, Py = Pyrope). We have determined the location of this reaction between 5 and 11 GPa in a multi-anvil apparatus, using crystalline starting materials and sealed Pt capsules. Reaction (2) lies at higher pressures for a given temperature than does the Di-bearing reaction (1). Ca and Fe present in the natural system could go into both the carbonate and the garnet, with

counteracting effects on the position of the curve in P-T space. We conclude that this reaction remains a potential candidate for carbonating eclogites and that evaluation of the effects of both Ca and Fe are required. Towards this end, we are extending this study to the CMAS-CO₂ system.

Siderophile elements partitioning between metal and silicate liquids in model C1-chondrite

(Y. Thibault)

Isobaric (P=5GPa, T=2300-3200K) and isothermal (T=2500K, P=3-12GPa) experiments were performed to distinguish between temperature and pressure effects on the partitioning of Ni and Co between metal and silicate liquids ($D_{X}^{met-sil}$). The starting material was a C-1 chondrite analogue in the CaO-MgO-Al₂O₃-FeO-SiO₂-Fe-Ni/Co system. At these high pressures and temperatures, $D_{Ni}^{met-sil}$ and $D_{Co}^{met-sil}$ reach values 4 and 20 times respectively lower than those observed at atmospheric pressure and 130°C. Increasing pressure and temperature both result in lowering $D_{Ni}^{met-sil}$ and $D_{Co}^{met-sil}$. Pressure is, however, significantly more efficient in the P-T interval investigated. Thus, the observations of Keppler and Rubie (1993, Nature, 364, 54) of pressure-induced coordination changes of Co and Ni ions in albite melt might also apply to Mg- and Fe-rich melts, resulting in much less siderophile behavior at high pressures. Based on available results on partitioning at atmospheric pressure, siderophile elements with different valencies than Ni²⁺ and Co²⁺ in silicate melts could have significantly different behavior. Thus, we are now investigating the effect of pressure and temperature on the partitioning of other siderophile elements with higher oxidation states such as W⁶⁺ and Ga³⁺.

Projects by external users:

The majority of projects involving external users are of a service nature; the researcher sends the starting material to the laboratory; it is loaded and run by the staff here, and then the run product is returned to the researcher. This service component is an essential component of the research being conducted in the laboratory. In addition, the staff of the laboratory welcomes visiting researchers, those who prefer a more "hands-on" approach to experimental work.

Roger Mitchell (Lakehead University, Thunder Bay, Ontario) has been working on two projects involving the Superpress. The first project examined the stability of titanium silicates at high pressure. The second project is to study the phase relations of lamproites at high pressure.

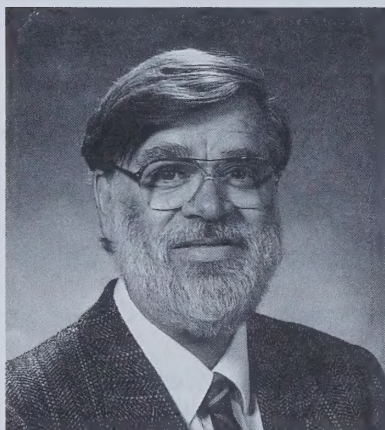
Alan Edgar (University of Western Ontario) has been working on the phase relations of lamproites with Roger Mitchell.

Michael Fleet (University of Western Ontario) and Grant Henderson (University of Toronto) have been studying alkali silicate glasses quenched from high pressure with a variety of spectroscopic techniques.

Dante Canil (University of Victoria) visited in July 1994 and conducted experiments on the kinetics of nitrogen aggregation in diamond.

6.2 Isotope Studies, Geomagnetism, Geothermics and Geology

6.2.1 Electromagnetic Studies (F.W. Jones) e-mail: wjones@terra.phys.ualberta.ca



F.W. Jones

Magnetotelluric Studies in Portugal

F.W. Jones, A. Correia

The region of the intersection of the Messejana Fault and the Ferreira-Ficalho Overthrust in southern Portugal proves to be an extremely interesting area in terms of its electrical characteristics.

Both 2D and 3D electromagnetic models have been constructed for the study area and results from these compared with the field data from the 34 measurement sites. When the 2D and 3D model results are compared, it is found that some geoelectric characteristics found in the 3D model are not apparent, or even suspected from the 2D results. The 2D analysis along profiles near the boundaries of the study area does not give any indication of the 3D nature of the nearby region. Comparison between field data results and the 3D model results indicates, however, that the main geoelectrical characteristics of the region are evident in the response of the 3D model, despite its lack of refinement. It is apparent that 2D analysis can be misleading, even on a scale of 10 to 50 km.

Although high heat flow densities have been reported to exist in the study area, the magnetotelluric data suggest that these values do not represent the thermal state of the crust in the region. Thermal modelling of the area indicates that temperatures at depth calculated from geotherms based on the reported heat flow densities will give electrical sensitivities at depth is consistent with those observed from the magnetotelluric measurements. As a consequence it is found that care must be taken if the reported temperatures are to be extrapolated to greater depths in the area. It is thought that water flow from depth may explain the high heat flow densities in the area.

Mohr circles are being calculated from the impedance tensor elements from the magnetotelluric data. The characteristics of these circles are different northeast of the Ferreira-Ficalho Overthrust compared with southwest of it. Various parameters such as anisotropy and dimensionality for the measurement sites in the area are being investigated through the Mohr circle approach.

Magnetotelluric Studies in Northern Saskatchewan

F.W. Jones, A. Kalvey, A. Correia

Thirteen magnetotelluric sites were occupied along highway 914 north of Pinehouse Lake in northern Saskatchewan during 1992 and 1993. Analysis of these data has shown that an extremely low resistivity zone exists near the boundary between the Mudjatik and Wollaston domains. The relationship of this feature to the North American Central Plains (NACP) conductivity anomaly is not yet known.

Magnetotelluric Studies in West-central Alberta

F.W. Jones, A. Kalvey

Work continues on the data from the 13 magnetotelluric sites in the Hinton-Edson-Robb area of west-central Alberta. The data indicate zones of relatively low resistivity that are probably associated with saline fluids in the sediments. Furthermore, the basement resistivity appears to be relatively low (generally less than 1000 ohm.m).

Magnetotelluric Studies and Lithoprobe

F.W. Jones, R.D. Kurtz, D. Boerner, J. Craven, H. Pelletier, P. Martin, S. Rodenay, A. Correia

Dr. Jones and H. Pelletier from the University of Alberta joined with Geological Survey of Canada personnel in the acquisition of electromagnetic data along the Lithoprobe Alberta Transects. During the summer of 1994, measurements were made at 95 sites using the Long Period Intelligent Magnetotelluric System (LIMS) developed at the GSC. Together with previous data, there are now data from 132 long period sites in the central and southern parts of the basin in Canada. It is found that the electromagnetic response is related to lithological contrasts in the basement and correlates with strike directions inferred from potential field data. Two-dimensional inversions indicate prominent linear conductive features in the electrical basement.

Electromagnetic and Thermal Modelling

F.W. Jones, A. Correia, A. Kalvey, M. Eastman

Both 2D and 3D electromagnetic modelling have been applied to the magnetotelluric data from Portugal, and 2D modelling has been used in the interpretation of the data from west-central Alberta. The work on the northern Saskatchewan data is in progress.

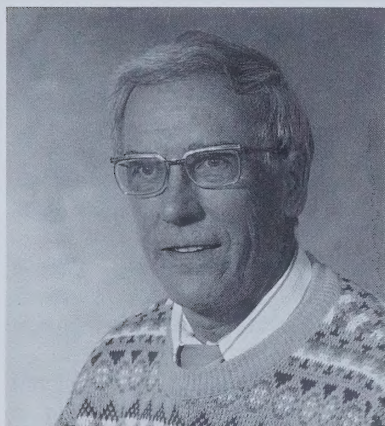
One-dimensional thermal models have been used to investigate the possible thermal nature of the crust in southern Portugal and its relationship to the electrical nature there is inferred from the magnetotelluric data, as well as to investigate the implications of geothermal profiles based on various types of data.

Geothermal Studies in Eastern Canada

F.W. Jones, A. Correia

Data from the Jeanne d'Arc Basin in offshore eastern Canada have been used for the basis of a comparison of geotherms calculated using data from different sources. For this basin at least, it is found that using assumed thermal conductivity values for the various rock types based on published values is misleading and can result in heat flow density estimates that can be one-half those found using conductivities based on measured values from rocks from some of the wells in the basin. These heat flow differences can lead to large differences in the extrapolated temperatures at depth.

6.2.2 Earth Tides and Tilts (Jim Rogers)



J.S. Rogers

Four mercury-level tiltmeters have been installed at the OPAL detector of the LEPC (Large Electron Positron Collider) ring at CERN in Switzerland. In the LEP machine, positively and negatively charged particles are accelerated to high energies as they travel around a circular track and are allowed to collide in a detection chamber where the products of the collision can be detected and their characteristics studied. However, energy and luminosity fluctuations occur in the particle beam, and the source of these fluctuations is unknown. The circular ring of the LEP machine is in an underground circular tunnel of 27 km circumference and lies approximately 100 m below the surface. It is thought that the warping of the circular track due to earth motions may cause the beam variations.

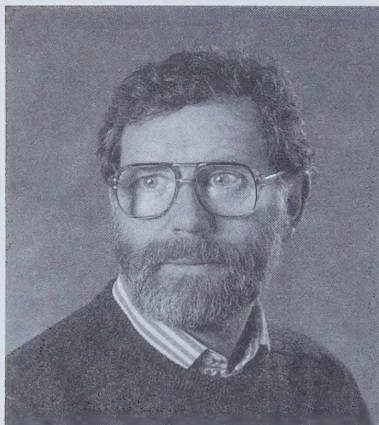
The charged particle beams are guided by electromagnets along the ring. The magnets are precisely placed on the ring and their magnetic fields carefully controlled in order to position the beams and to focus them properly at the intersection points. Any relative movement of the magnets will displace the beams, and so will cause movement of the intersection points and/or broadening of the beam with consequent change in luminosity, energy, and product detectabilities.

Since the dimension of the ring of electromagnets is large, relative earth movements can occur that can cause relative movements of the magnets and thus disturbances to the charged particle beam. Relative earth movements can be caused by tides in the 'solid' earth, tectonic adjustments, earthquakes, temperature variations, snow cover or rainfall. It is important to monitor these earth movements around the ring and to correlate these with changes in beam characteristics in order to properly interpret the experimental results from the collision experiments.

Two tiltmeters have been installed in the beam tunnel on each side of the OPAL detector and have operated for approximately 8 months. It is found that the 'along-beam' tilts on the two sides of the detector correlate well, whereas the tilts perpendicular to the beam do not correlate. Work is now underway to investigate correlations between the tilt data and the beam control parameters.

6.2.3 Paleomagnetism and Rock Magnetism (Ted Evans)

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M.E. Evans

Chinese Loess Plateau

M.E. Evans, F. Heller*, N.W. Rutter**, Z.L. Ding***, T.S. Liu***

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**Department of Geology, University of Alberta

***Institute of Geology, Academia Sinica, Beijing, China

Work on the use of magnetic susceptibility as a paleoclimatic proxy is continuing. So far, the focus has been on the excellent section at Baoji, but material from other sites has been studied in collaboration with the Zürich group. Two papers have been published dealing with the variation of susceptibility and other mineral magnetic properties across the Loess Plateau. These point strongly to the conclusion that bacterial magnetite is the source of the magnetic enhancement which, in turn, records climatic variation. Particular attention has been paid to the frequency dependence of susceptibility, which indicates that the upper and lower grain-size boundaries are essentially invariable, not only across the Loess plateau, but also in the Tajik loess (central Asia), and even in soil chronosequences on the California coast.

During the summer, Prof. Friedrich Heller spent 5 weeks in the Institute in order to further our collaborative work on Quaternary sediments in China and the Czech Republic. This visit also provided a critical opportunity for us to prepare an invited review article on loess magnetism for *Reviews of Geophysics*.

Siberian Loess

M. E. Evans, N.W. Rutter*, J. Chlachula*

*Department of Geology, University of Alberta

Two field seasons at a site in southern Siberia have yielded high-quality remanence and susceptibility data. The most complete profile consists of 34 metres of loess and paleosols at a site in the upper Yenisey River valley. In the summer of 1993, palaeomagnetic samples were collected at 10 cm intervals throughout the entire section. A follow-up investigation in 1994, focused on the 6.6 m representing the last interglacial (220 samples taken at 3 cm intervals). Susceptibility maxima correlate with intervals of intensive loess deposition, whereas minima correspond stratigraphically to the most developed pedogenic horizons. This is the complete opposite of the pattern found in the Chinese loess, and we have therefore embarked on a series of mineral magnetic investigations aimed at elucidating this puzzle.

The remanence results indicate normal polarity throughout (NRM: $D = 0^\circ$, $I = 58^\circ$, $k = 85$, $a_{95} = 0.8^\circ$; 10mT: $D = 352^\circ$, $I = 62^\circ$, $k = 82$, $a_{95} = 0.9^\circ$). However, in the upper part of the section, two ~50cm-thick intervals containing systematic directional deviations are found in undisturbed geological contexts. These two excursions are stratigraphically separated by a radiocarbon date of $30,400 \pm 700$ B.P. on spruce wood. This raises the possibility that these Siberian features may correspond to part(s) of the Lake Mungo and/or Laschamp-Olby Excursions.

Archeomagnetism

M. E. Evans, L. Jiang

A review article, based on an invited keynote address presented by Dr. Evans summarizing the entire corpus of archeomagnetic results from the Mediterranean region, is currently in press as part of a special volume being published by the Geological Society (London, England).

For his M.Sc. project, L. Jiang investigated the mineral magnetic properties of typical (and atypical) archeological materials, drawing on the large Italian, Greek, and North African collection available in-house, but also including material representing a broad time range of Chinese archeological sites.

Mackenzie Delta Project

M. E. Evans, Y. Wang, S. Dallimore**, J.V. Matthews***

**Alberta Research Council, Edmonton*

***Geological Survey of Canada, Ottawa*

The paleomagnetic potential of permafrost samples has been investigated as part of a major drilling project in the Mackenzie Delta. A total of 357 sub-samples taken from two long cores (Taglu, 414m; Kumak, 262m) have been investigated. Remanence and susceptibility were measured in the field while the samples were still frozen. Profiles of susceptibility provide passive markers allowing lateral correlation; in this case they imply that the average accumulation rate at Taglu is ~50% greater than at Kumak which lies 15km to the southwest. Polarity reversals were found in both cores. The Matuyama-Brunhes boundary occurs at depths of 152m and 110m at Taglu and Kumak respectively; corresponding depths for the Gauss-Matuyama boundary are 356m and 243m. The chronology based on these data suggests that a major change in sedimentation history occurred about 1.3Ma ago. This feasibility study thus suggests that paleomagnetism has chronological potential in permafrost environments which are currently assuming some importance in frontier hydrocarbon exploration and as natural gas hydrate reservoirs.

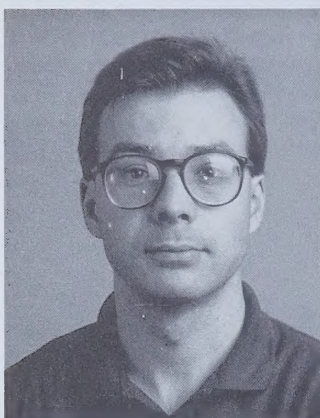
Cretaceous-Tertiary Boundary

*M.E. Evans, J.F. Lerbekmo**

**Department of Geology, University of Alberta*

The Canadian Continental Drilling Program cored three holes (each ~170m deep) to intersect the Cretaceous-Tertiary boundary in Alberta, Saskatchewan and Manitoba. These were sampled for paleomagnetic studies, and resulted in clear magnetostratigraphic zonation. With the aid of palynological control, it was possible to recognize Chrons 28 to 32 (possibly 33) in the various cores, although significant hiatuses are present. These results are important in establishing suitable chronological control for this inter-disciplinary project aimed at improving understanding of the so-called K-T biological crisis and its actual causal event(s).

6.2.4 Mass Spectrometry and Isotope Studies



Rob Creaser

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Natural High-Temperature Pelite Melting and Peraluminous Granite Generation: a case for Nd isotopic disequilibrium during crustal anatexis?

(R.A. Creaser, T. Chacko)

Granite and associated high-grade metasedimentary enclaves from Pelican Rapids (PR) in NE Alberta are part of the regional 1.93 Ga Slave Batholith from the 1.9 - 2.0 Ga Taltson Magmatic Zone. The outcrop at PR comprises three phases (leucosome, Phase I, Phase II) of granite containing large, refractory enclaves of pelitic to psammitic paragneiss. P-T estimates using thermobarometry and oxygen isotope thermometry are 6-8 kbar, 900-1000°C for granites and enclaves. Field relationships, the strongly peraluminous granite composition and the refractory enclave nature strongly suggest a melt-restite relationship between granites and enclaves. This is supported by O isotopic data which shows a similar range of values across the outcrop ($\delta^{18}\text{O} = 9.1 - 10.5\text{‰}$). Also, the geochemistry of pelitic enclaves suggests up to 50% melt removal from a shale protolith. Despite the high temperatures and extensive melting, the granite compositions remain leucocratic, in accord with experimental melting studies of pelites. When compared with published experimental results, granites from leucosome to Phase I to Phase II appear to represent sequentially higher degrees of partial melting from a pelite protolith; this is also deduced from their field abundances. Geochemical arguments also indicate this to be the case; particularly the REE and Th systematics which are strongly influenced by the melting behavior and solubility of monazite. Refractory pelitic xenoliths yield ϵNd_T values of -4 to -7. The leucosome and Phase I granites yield ϵNd_T values of -10 to -11, and Phase II granite -5 to -6. At face value, these data indicate that the leucosome and Phase I granites are unrelated to the refractory enclaves, despite intimate field relationships. Alternatively, these data can be explained by partial melting of a pelite where the Nd isotopic (and REE) budget are controlled by the melting behavior (solubility) of 2 mineral phases with vastly different Sm/Nd and Nd isotopic compositions at the time of melting; garnet and monazite. Thus, at the early stages of partial melting, significant isotopic contrasts between a (total-rock) protolith value and partial melts can be produced, followed by later similarities (Phase II vs. refractory enclaves) as protolith heating continues and diffusion- and recrystallization-driven isotopic equilibration occurs. This explanation requires that protolith heating and initial melting occur on timescales significantly less than those required for inter-mineral diffusional equilibration in the protolith.

Early Paleozoic Evolution of the Yukon-Tanana terrane, SE Yukon: Geochemical and Nd Isotopic Constraints from the Teslin Tectonic Zone

(R.A. Creaser, P. Erdmer, S.L. Grant, R.A. Stevens)

The Teslin Tectonic Zone (TTZ) is a belt of highly strained metamorphic rocks from the Yukon-Tanana terrane (YTT) of SE Yukon. It occupies a critical location in the Cordillera, at the boundary between autochthonous North American Continental Margin (NACM) rocks and accreted terranes of arc or oceanic affinity to the west. We have completed a detailed investigation of Nd isotopic and geochemical characteristics of the (pre-Mississippian) TTZ metasedimentary rocks in order to constrain their origin, tectonic setting and possible relationship to NACM strata. At the base of exposed stratigraphy a micaceous quartzite unit has ϵNd_0 values of -24 to -29 with T_{DM} ages of 2.5 - 2.8 Ga indicating a source region(s) with a long crustal residence history. Major and trace element data indicates a provenance of felsic continental crust. These data therefore allow, but do not demand, a NACM origin for these rocks. Overlying the micaceous quartzite unit is a graphitic phyllite unit, which has ϵNd_0 values of -7 to -18 and T_{DM} ages of 1.5 - 2.2 Ga. Geochemical features indicate a provenance with a higher component of chemically primitive crust than the underlying unit. Higher in the metasedimentary succession graphitic shales and semi-pelites occur associated with small greenstone units. These rocks have ϵNd_0 values ranging from -7 to +1 with T_{DM} ages of 0.9 - 1.5 Ga. When calculated at a minimum deposition age of 350 Ma, ϵNd values range up to +4. Geochemical characteristics indicate a primitive crustal source (basaltic-andesitic), and the Nd isotopic data suggest this had a short crustal residence history. The TTZ metasedimentary strata therefore preserve a temporal evolution in provenance from a passive continental margin environment to one of an active magmatic arc. The presence of metasedimentary rocks with a source of young, chemically primitive crust implies that if the YTT was originally linked to North America in the Paleozoic prior to Mesozoic rifting, the rocks now seen in the TTZ were likely distal facies near the limit of continental influence on sedimentation, and that pre-Mississippian arc activity likely characterized outboard the continental margin of North America at this time.

Osmium isotope systematics of modern arc mantle lithosphere

(R.A. Creaser, A.D. Brandon)

The subduction of oceanic crust is a fundamental process which influences the geochemistry of the mantle and arc magmas. Element transport from the subducted slab to the overlying mantle wedge is well-established, but significant amounts of material are also returned to the deeper mantle. The Os isotopic system presents an interesting geochemical case as a result of the vastly different geochemical behavior of Os relative to other isotopic tracers (Sr, Nd, Pb). Because both sediments and basalts of the oceanic crust have very high Re/Os relative to the mantle, their Os isotopic compositions evolve very rapidly, and subducted oceanic crust will have highly radiogenic Os isotopic compositions. The fate of this radiogenic Os is, at present, poorly constrained. This Os, if removed from the oceanic crust in subduction zones, could lead to radiogenic Os isotopic compositions in the mantle wedge and/or arc magmas. If the Os is not removed from the subducted oceanic crust, then radiogenic Os could be returned to the deep mantle. Recent studies of Os isotopic compositions in ocean island basalts have invoked a recycled crustal component to account for radiogenic Os isotopic compositions observed, suggesting return of radiogenic Os to the deep mantle via subduction zones. We have analyzed spinel peridotite xenoliths from the Japan arc (Ichinomegata) and Cascade arc (Simcoe) for Os isotopic compositions. Sulfur isotope evidence indicates interaction of these peridotites with subduction-derived fluids/melts. Ichinomegata peridotites show values of $^{187}\text{Os}/^{188}\text{Os}$ from 0.12440 to 0.1267 ($\gamma\text{Os} = -3$ to -1). A single sample from the Cascade arc shows a similar isotopic composition of 0.1247 ($\gamma\text{Os} = -2.5$). These isotopic compositions are less radiogenic than average mantle values, and are similar to average Os isotopic compositions for the depleted mantle, determined from abyssal peridotites. The Os data obtained indicate little or no transport of Os from the subducted slab for the cases studied, and imply return of radiogenic Os to the deep mantle. Subducted oceanic crust is therefore a viable source of radiogenic Os observed in some ocean island basalts.

Geochemical and isotopic study of volcanic and granitoid rocks from Ghost Lake area (Wijnnedi Lake area), Slave structural province, NWT

(K.Yamashita, R.A. Creaser)

The Ghost Lake area is located in the southwestern of Slave structural province, approximately 150km north of Yellowknife. Rocks exposed in this area consist of metamorphosed sedimentary and volcanic rocks of Yellowknife supergroup, granitoid rocks of syn-volcanic age (in part older than Yellowknife supergroup?) and younger syn- to post-deformational granitoids rocks. Samples from syn- to post-deformation granitoids and one sample from both metavolcanic rocks and syn-volcanic plutons were selected for geochemical and isotopic analysis. Metavolcanic and syn-volcanic pluton dated at 2673 Ma and 2654 Ma respectively, have geochemical characteristics similar to those from the Contwoyto Lake area, central Slave province. ϵNd_T values are 1.0 and 0.9 respectively, indicating a minor role of older crust in their genesis. Compared to the older units, the trace element geochemistry of 2605-2589 Ma syn- to post- deformational granitoid rocks are much more variable. However, these geochemical characteristics also resemble that of granitoid rocks of similar age from Contwoyto Lake area, and may suggest a broadly similar petrogenesis. Their ϵNd_T values, however, are all positive, as opposed to positive to strongly negative signatures seen in most syn- to post-deformational granitoids from the western Slave province. Broadly similar results have been obtained from equivalent rock units south of Ghost Lake, in the McNaughton Lake area. This suggests that there are significant variations in Nd isotopic signatures both in east-west and north-south direction across the Slave province, and that crustal domains and tectonic histories in the western Slave province are more complex than some current evolutionary models propose.

Nd isotopic study of the Hanikahimajuk Lake area, Slave structural province, NWT

(K.Yamashita, R.A. Creaser, J.E. Jensen)

The Hanikahimajuk Lake area is located in the northwestern margin of Slave province, approximately 425 km north of Yellowknife. Rocks exposed in this area consist of 3.4 Ga tonalitic and gabbroic basement, 2.7 Ga mafic to felsic volcanic rocks, syn-volcanic diorites and younger 2.55 Ga granites. The basement tonalite/gabbro has an ϵNd_T values ranging from 1.7 to -0.5 with T_{DM} ages of 3.5 Ga. Their ϵNd values at 2.7 Ga ranges from -4.1 to -10.5. The ϵNd_T values of volcanic rocks range from 2.5 to -1.2, with more felsic rocks having progressively lower ϵNd_T values. Positive ϵNd_T values of most mafic to intermediate volcanic rocks suggest their derivation from the depleted mantle source with minor assimilation of older crust, whereas lower ϵNd_T values of some intermediate to felsic rocks indicate a significant role of older crust in their genesis. This observation argues against models which suggest the older crust in the western Slave province was juxtaposed to a younger volcanic arc, represented by central-eastern Slave province, during the assemblage of the craton. The ϵNd_T values of syn-volcanic diorites range from 1.1 to -2.2, which generally overlaps with that of intermediate to felsic rocks from the volcanic belt, suggesting that these rocks are likely the plutonic equivalents to the volcanic rocks. One sample of metasediment was also analyzed and gave an ϵNd_T value of -0.4. This value overlaps with that of volcanic rocks, suggesting that major source of the detritus was rocks from the volcanic belt, with minimum contribution from the older basement. The ϵNd_T values of younger granites ranges from 1.6 to -2.2. These values overlap with that of other post deformational granites from the western Slave province.

U-Pb and Sm-Nd isotopic study of metasediments from western Slave province, NWT

(K. Yamashita, R.A. Creaser, M. Villeneuve)

U-Pb and Sm-Nd analysis of metamorphosed sedimentary rocks from the western Slave province is currently in progress. The main objectives of this research are, (1) to investigate the usefulness of Nd isotopes as a tool to search for pre-2.7 Ga crust, (2) apply this to regional metasediments to assess the extent of pre-2.7 Ga crust in the western Slave province and (3) use Nd isotopic signatures of the sediments with different ages to study temporal evolution of sediment provenance. Because the bulk isotopic composition of metasediments represents the average isotopic composition of the provenances, we speculate that Nd isotopes in sediments can be used to select the samples which may contain traces of older crustal material. Going through this step prior to U-Pb geochronology may be particularly important because both the amount of sample and the time required for the analysis of Sm-Nd isotopes is much smaller than that of U-Pb geochronology. For each sample that was analyzed for Sm-Nd isotopes, 7 to 9 detrital zircons were selected for U-Pb geochronology and analyzed by M. Villeneuve at the Geological Survey of Canada. Although this study is still at an early stage, the following comments can be made. (1) $\epsilon\text{Nd}_{2.68 \text{ Ga}}$ values of metasediments generally decrease as the average U-Pb age of detrital zircon increase. For the samples analyzed so far, those which contain pre-3.0 Ga zircon have $\epsilon\text{Nd}_{2.68 \text{ Ga}}$ values < 0 , while those without pre-3.0 Ga zircon have $\epsilon\text{Nd}_{2.68 \text{ Ga}}$ values > -1 . (2) There is a positive correlation between T_{DM} age and the age of oldest zircon from each sample. A similar correlation is also observed between average age of zircons and T_{DM} , but not as pronounced. (3) There is a variation in $\epsilon\text{Nd}_{2.68 \text{ Ga}}$ values between different units within a single turbidite sequence. As previously described, this may represent unmixing of components from different provenance during sedimentary transport and sorting.

Isotopic and Elemental Systematics of Sr and Nd in Ordovician Conodonts and Other Biogenic Fossils

(C. Holmden, R.A. Creaser and K. Muehlenbachs)

Conodonts are teeth-like microfossils thought to have composed the feeding apparatus of an extinct eel-like organism known from Cambrian to Triassic strata. They are primarily studied as index fossils for purposes of relative age dating and stratigraphic correlation. However, it has long been recognized that conodonts, being less soluble than calcitic fossils, may provide a more reliable record of pre-Mesozoic paleoseawater chemistry. Pristine coniform and ramiform conodonts ($\text{CAI} = 1.0\text{--}1.5$), inarticulate brachiopods and conulariids from a single handsample (collected by S.A. Leslie, Ohio State University) have been analyzed for their Sr and Nd concentrations and isotopic abundances. Strontium and neodymium concentrations show a strong negative correlation between the various fossil taxa. Electron microprobe analysis reveals similar antithetic distributions of Sr and Nd within single ramiform and coniform conodonts possessing basal body material. Sr isotopic analyses gave the surprising result that no single value of $^{87}\text{Sr}/^{86}\text{Sr}$ is preserved among the fossil population, in contrast to the expectation of a unique seawater $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. Rather, the Sr isotopic data define a mixing array between Ordovician seawater and a (radiogenic) diagenetic fluid end-member. Contrasting the Sr results, $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are identical for all fossil taxa (0.51131 ± 0.00001 at 454 Ma). This is so despite the large range in Nd concentrations found, and that the Nd content of marine apatites is acquired almost entirely post-mortem. Although the uniformity in apatite $^{143}\text{Nd}/^{144}\text{Nd}$ ratios is consistent with contemporaneous seawater as the dominant source of Nd, conodont $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are generally unreliable. Future efforts will be directed towards understanding the relationship between Nd incorporation in conodont apatite and sites of Sr exchange in ramiform conodonts.

Paleosalinity Determination in Ancient Brackish Water Deposits Using the Isotope Paleohydrology of Sr and O

(C. Holmden, R.A. Creaser and K. Muehlenbachs)

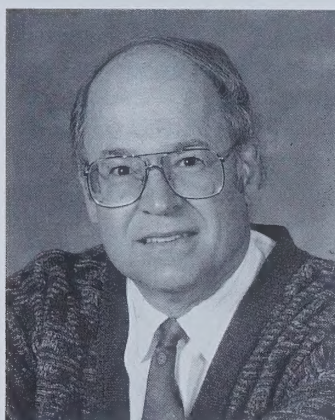
Studies of seawater-freshwater mixing in modern estuaries has demonstrated the conservative behavior of dissolved Sr and its isotopes with salinity. Therefore, Sr isotope variations recorded in carbonate fossil shells from ancient estuarine deposits may be used to determine relative paleosalinities, which in turn can provide constraints on the depositional environment. The early Cretaceous Mannville Group, Western Canada Sedimentary Basin, contains numerous examples of brackish water deposits formed in a complex hydrological system at the interface between north flowing rivers of the early Cretaceous foreland basin drainage system and southerly transgressing waters of the Moosebar-Clearwater epicontinental sea. One of these deposits, the Ostracode Zone, contains abundant carbonate fossils. Isotopic analyses of Ostracode Zone fossils and contemporaneous marine and fresh water fossils are being used to reconstruct the isotope paleohydrology of the Ostracode sub-basin to estimate paleosalinity of the original Ostracode waters through isotopic mass balance constraints. Although it is widely believed that the Ostracode Zone was deposited under brackish water conditions, our isotope results are consistent with an entirely fresh water depositional setting. The very uniform O isotopic composition of Ostracode Lake waters indicates either a single well mixed lake or a series of hydrologically open lakes. In the absence of a significant marine component, Sr and C isotopic compositions of Ostracode Lake waters were strongly influenced by chemical weathering of Mississippian and Devonian carbonates comprising paleotopographic highs within the basin. These isotope paleohydrological methods provide sedimentologists, paleolimnologists and paleoecologists with a powerful new tool for distinguishing marine, brackish and fresh water depositional environments, calculating relative paleosalinities in estuarine and estuarine-like depositional systems, determining salinity tolerances of extinct fossil taxa, and tracing changes in the water balance of ancient lakes.

Isotopic Evidence of Magma Mixing in the Campanas Igneous Complex, La Rioja Province, NW Argentina

(W.A. Perez, R.A. Creaser, T. Dunn)

The role of magma mixing in the generation of calc-alkaline intermediate magmas has been debated for many years. We are conducting a detailed isotopic and geochemical study of an area that shows very clear field evidence of mafic-felsic magma interaction; the Campanas Igneous Complex (CIC). The CIC comprises the Campanas Granite (CG) which is intruded by mafic dykes and zoned mafic intrusions (ZMI). The ZMI, which consist of gabbroic cores surrounded outwards by concentric rings of diorite, tonalite and granodiorite, extend in an approximately 6 Km long N-S band along the central axis of the CIC. Major and trace element abundances vary systematically from the core of each ZMI to the surrounding CG. Samples of CG close to the ZMI have lower abundances of SiO₂ and incompatible elements than samples far from the ZMI, reflecting chemical interaction with the ZMI. The ZMI are heterogeneous in composition and contain mineral disequilibrium features such as reverse zoned plagioclase and quartz ocelli. U-Pb zircon ages from the CG, and tonalites and granodiorites from the ZMI provide a concordia age of 468 ± 3 Ma. This age is coincident with the K-Ar hornblende age of 459 ± 24 Ma from the tonalite facies. Twenty-three Sr and Nd isotope analyses of samples along a profile from the gabbro to the granite define a mixing curve in Nd-Sr isotopic space with $\epsilon_{\text{Nd-T}}$ variations from +4 to -3 and $\epsilon_{\text{Sr-T}}$ variations from -60 to +60. This wide isotopic variation occurs in samples separated by each other in the ranges of only few a meters, highlighting the absence of diffusion-controlled isotopic equilibration in such mixing systems. Petrographic, geochemical and isotopic data suggest that the evolution of the complex was controlled by fractional crystallization and replenishment of mafic magma inside a granite magma chamber, followed by extensive magma mixing between the CG and the fractionated end-members of the ZMI to produce intermediate calc-alkaline rocks.

6.3 Space Physics



G. Rostoker

6.3.1 Solar-Terrestrial Relationships (Gordon Rostoker) e-mail: rostoker@space.ualberta.ca

The Space Physics Group has continued to sponsor a very active program in the study of the interaction of the solar wind with the Earth's magnetosphere, with emphasis on the analysis of data from the large ground-based instrument array CANOPUS and the recently initiated SuperDARN HF radar experiment, and on the development of MHD computer codes to simulate the development of auroral arcs.

Over the past year Dr. Rostoker has continued his studies of magnetospheric substorms, addressing the question of acceleration of ring current particles (together with Dr. William Liu) and considering the possible mechanisms for that acceleration in the context of the renovated boundary layer dynamics model. The main thrust of the research this year was the pursuit of the concept that whether or not a substorm expansive phase was responsible for the acceleration of ring current particles that contribute to Dst depended, not so much on the magnitude of the expansive phase magnetic perturbation but rather on how close to the Earth the onset was initiated. This thesis was explored at the International Conference on Magnetic Storms (held in Rikubetsu, Japan) and at the International Conference on Trapped Radiation (held in Taos, New Mexico). At present, further studies are underway to demonstrate that only when the equatorward border of the auroral oval reaches rather low latitude are substorm expansive phase onsets associated with a growth in Dst.

Dr. William Liu has explored the nature of the acceleration process, together with Dr. Rostoker. In his approach, Dr. Liu argues that acceleration takes place iteratively in a sequence of substorm expansive phase onsets which involve a number of cycles in which the near-Earth magnetotail field is slowly stretched (viz. growth) and suddenly returned to a nearly dipolar configuration (viz. expansion). The mechanism involves non-adiabatic behaviour of ions in which a combination of pitch angle scattering and acceleration through the action of inductive electric fields can lead to those ions eventually achieving energies of several hundred keV.

Stimulated by the outages of the Canadian Anik E1 and E2 communications satellites as a consequence of deep dielectric charging, Dr. Rostoker has commenced a study of how near-

relativistic electrons (with energies from hundreds of KeV to MeV) come to be found in the geostationary orbit environment which is normally not the site of such electron fluxes. Early investigations using the CANOPUS instrument array operated by the Canadian Space Agency have revealed that the appearance of the high energy fluxes is intimately associated with the occurrence of extremely large amplitude Pc 5. ULF magnetic pulsations in the morning hours. It is thought that the large amplitude fluctuating electric fields associated with the pulsations are responsible for the transport of energetic electrons from the outer radiation belt radially outward until, if the activity persists, it envelopes the region of geostationary orbit and beyond. The delay time between the onset of the pulsations and the appearance of the energetic electrons at geostationary orbit is ~2-3 days and the onset of the pulsations appears to be related to the appearance of high speed solar wind streams possibly associated with coronal holes. This research is being carried out together with Ms Susan Skone and with Dr. D.M. Baker of the University of Colorado.

Mr. Martin Connors, a doctoral student under the supervision of Dr. Rostoker is continuing his exploration of techniques to model the overall ionospheric and field-aligned current distribution found on field lines threading the auroral oval. Mr. Connors has developed and is utilizing a new technique which uses primarily ground-based magnetometer data and which attempts to fit to those data a proper forward model of the global current system. The results are controlled by additional input data from orbiting satellites and from control ground stations whose data are not used as input for the model routines. It is expected that this research will be completed toward the end of 1995, and will have as its product a method of modelling which complements the KRM and AMIE models which call for the use of data bases other than ground based magnetometers for their input data.

6.3.2 Substorms (John Samson)

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J.C. Samson

Dr. Alex MacAulay together with Dr. J. C. Samson have been investigating the stability of auroral arcs to instabilities driven by shear flows (Kelvin Helmholtz or KH) and pressure gradients (ballooning or interchange). This work is motivated by a desire to understand the structuring of auroral arcs ubiquitously observed during active times, and by an interest in finding a triggering mechanism for the substorm intensification onset.

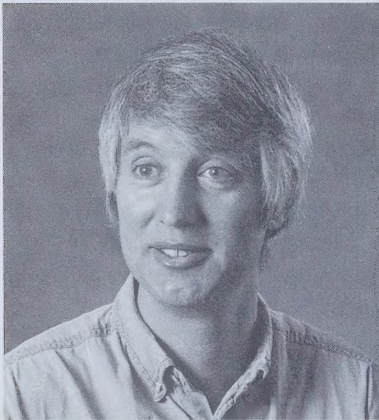
There is considerable experimental evidence that auroral field lines map from the ionosphere to the inner edge of the plasma sheet or nightside cusp region. During active times, large earthward pressure gradients are produced in this region as plasma convected towards the earth is adiabatically compressed. This pressure gradient represents a source of free energy, which may be tapped to drive ballooning or interchange type instabilities. Also, the electric fields

present in the inverted V auroral potential structure imply the presence of sheared fluid flows (at the $E \times B$ velocity) which provide drive for the Kelvin-Helmholtz instability.

In general both of these drives are active, though the pressure gradient drive is usually more than balanced by gradients in the flux tube volume (so that pure interchange is stable). We find for typical conditions that KH like instabilities may be excited, though they are unable to release the energy in the pressure gradient, at least within an ideal MHD treatment. These instabilities instead take energy out of the shear flow to drive interchange stable motions. Dr. MacAulay is presently investigating including the Hall term in Ohm's law which, by breaking the ideal MHD constraint, will hopefully overcome this problem and allow the free energy in the pressure gradient and stretched tail field to be released, and the intensification to be triggered.

6.4 Meteorology, Climatology and Geophysical Fluid Dynamics

6.4.1 Micrometeorology (John Wilson) e-mail: jwilson@geog.ualberta.ca



J.D. Wilson

Windflow Through a Plant Canopy on a Ridge

T.K. Flesch, S. Du, B. Wiens, R. Barrett

John Wilson visited C.S.I.R.O. Environmental Mechanics (Canberra) for three months. Finnigan and Raupach (CSIRO) have performed wind tunnel experiments on windflow through a tall plant canopy (height h_c) on a hill (half-length L , height H). Typically, such a flow lies outside the scope (legitimate region of L , H , z_0 parameter space, z_0 being the surface roughness length) of the linear, analytical theory for smooth hills (Jackson & Hunt, 1975, *Quart. J.R. Meteorol. Soc.*, **101**; hereafter JH) and its later refinements.

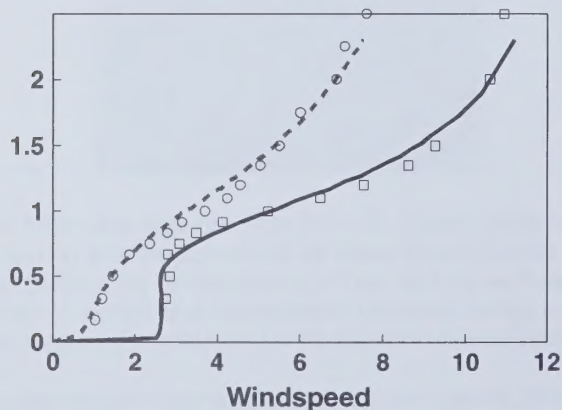


Figure 1. Observed (O) and modelled windspeed versus height (z/h_c), upwind (O) and at ridgetop (□)

Wilson derived exploratory mathematical descriptions of the observed flow, by matching a third, canopy layer to the 2-layer JH model. However wind changes over the hill were *not* small c.f. the upwind flow so that none of the linear treatments constructed were very successful. Therefore, non-linear numerical solutions (Fig. 1) were calculated: the streamwise-momentum equation was closed at first order, and forced by an imposed (measured; or theoretical, JH) pressure gradient, in order to simulate a hill flow. Since pressure was *provided*, this exercise amounted to the calibration of a first order closure, or a means of analysing of the experimental data to deduce a closure of minimal complexity. A preprint describing progress so far was published in conjunction with the 11th Symposium on Boundary Layers and Turbulence, March, 1995 (Am. Met. Soc.).

Random Flight Dispersion Modelling

Shuming Du (Ph.D. student) has used a trajectory model he derived (see last year's annual report of IGMSP) to deduce, from water channel, wind tunnel, and atmospheric dispersion experiments, the numerical value ($C_0 = 3.0 \pm 0.5$) of Kolmogorov's universal constant for the Lagrangian velocity structure function. C_0 appears in Kolmogorov's theoretical small-time estimate

$$D_{ij}(\Delta t) = C_0 \varepsilon \sigma_{ij} \Delta t \quad (1)$$

for the Lagrangian velocity structure function

$$D_{ij}(T) = \langle [u_i(t+T) - U_i(t)] [u_j(t+T) - U_j(t)] \rangle \quad (2)$$

Here the bracket $\langle \rangle$ denotes the expected value of its contents; u_i is the Lagrangian velocity; t and $t+T$ are arbitrarily separated times; ε is the rate of dissipation of turbulent kinetic energy; and Δt (in eqn 1) is a time increment satisfying $t_\eta \ll \Delta t \ll T_L$, where t_η is the Kolmogorov inner timescale, and T_L is the integral timescale. Our interest in C_0 stems from the fact that predictions of turbulent dispersion, if obtained using Lagrangian stochastic models consistent with eqn. (1), will depend strongly upon the value taken for it.

Measurements of Wind and Turbulence in Forest Cutblocks

Forestry Canada and partners have initiated experiments near Manning, Alberta to evaluate alternative harvest practises which aim to preserve the Spruce understory (for later harvest) at the time of hardwood (aspen) harvest. A concern is windthrow of the (previously sheltered) remnant spruce.

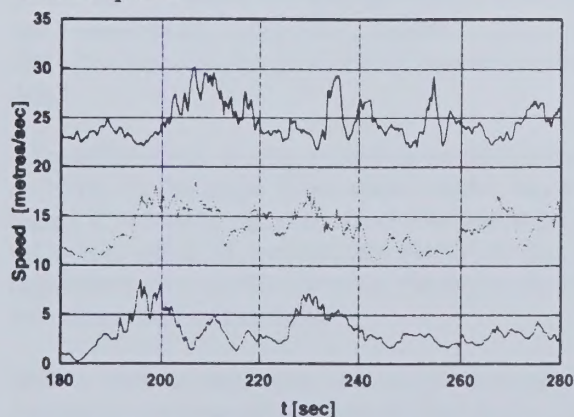


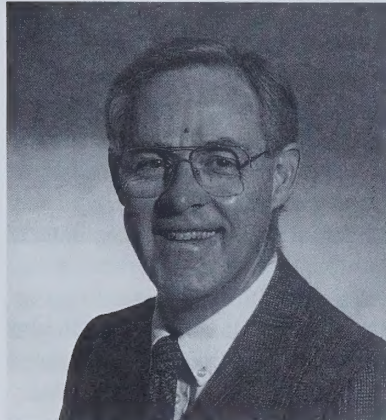
Figure 2: Windspeed vs. time on three towers; upwind edge, middle, and downwind edge of cutblock. Data offset by 10 m/s for upper two series.

In conjunction with this experiment, we are measuring windspeed at several sites, with a focus of the extreme winds. To look at local variation, Tom Flesch (Research Assoc.) has instrumented several towers traversing a cutblock. Time series of windspeed (all three components, sampling interval 0.1 sec, sampling duration 15 min), and of the wind-induced displacement of two remnant spruce, have been recorded during periods of extreme wind (e.g. Fig. 2). These data are under analysis by Barrett (M.Sc. student).

Woodsmoke Pollution and the Nocturnal Flow in a Valley

Woodsmoke pollution is a recurrent winter problem in Whitehorse (Yukon), during periods of light winds with poor mixing due to a ground-based temperature-inversion. Brian Wiens (M.Sc. student) has experimented with calculating nocturnal drainage flows, using a new weather/mesoscale forecast model ("MC2"), developed by Recherche en Prevision Numerique (RPN), Environment Canada. The aim was to study the behaviour of MC2 under the test conditions of, (i) a horizontally-uniform nocturnal boundary-layer developing at nightfall over an infinite flat plain, a case for which detailed 1-dimensional studies have been published; and, (ii) an idealised sinusoidal valley (symmetry *along* valley).

6.4.2 Icing, Refraction and Climate (Ed Lozowski)
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E.P. Lozowski

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Marine Icing

The interaction between ship motion and ice accretion is a non-linear feedback process, whose main features are: 1. the generation of freezing spray through the hydrodynamic interaction of the ship and the wave field, and 2. the non-uniform accretion of ice on the vessel, which changes the ship's centre of mass, moments of inertia, and hydrostatic particulars with a resulting change in its dynamics. We are investigating and simulating both of these processes.

The spray generation process has been investigated by the analysis of towing tank data obtained during our experiments with a model of the stern trawler Zandberg at the Institute for Marine Dynamics, NRC. The principal results of this work have been presented by Chung et al. (1995). In these experiments, the normalized spray mass distribution impinging on the deck was shown to exhibit an exponential distribution with longitudinal distance from the bow. Over the range of conditions considered, the total spray mass flux density was shown to behave as $v^\alpha h^\beta$, where v is the ship speed, h is the significant wave height, and α and β are 3 and 7 respectively. Using Froude number scaling and spray trajectory modelling, a full-scale spray flux equation for the Zandberg was developed, including the important effect of wind drag.

A numerical model of spray generation for the Zandberg has also been developed (Zakrewski et al. 1994). At this stage, it is a simple model, based on mass displacement by the hull, with tuning of the spray ejection velocity to match the experimental data. The model exhibits behaviour which is qualitatively similar to that observed in the experiments (similar dependence on v and h). However, the spatial distribution of the spray over the deck is not well represented by this model.

With a view to improving the model, generalizing it to other ships, and limiting its dependence on experimental data, we also undertook a series of fundamental experiments in which we examined the spray generated by the impact of a high buoyancy rigid sphere into a deep liquid. In these experiments also, a similar power law dependence of spray mass on

impact velocity was observed, and we are currently in the process of endeavoring to explain the physics of how the spray is produced and ejected.

We have developed a hierarchy of ship icing models with a view to understanding and exploring different aspects of the marine icing process. One of these, developed by Blackmore and Lozowski (1994), is an heuristic vessel icing model, which can be used to predict the overall ice accumulation rate on any vessel over a wide range of meteorological, oceanographic and operational conditions. This versatile model is positioned between purely statistical models and the computationally intensive ship-specific models. Its ice growth algorithm is based entirely on heat exchange between the droplets and the airstream during wind rafting of the spray. We have used it to demonstrate a possible severe icing mechanism, based on spray nucleation. The model results suggest that snowfall, frazil ice and low sea-surface temperatures can be critical factors in particularly severe icing episodes.

The focus of Blackmore's more recent work has been the physics and numerical modelling of spongy ice accretion. The model considers the dynamics of the falling liquid film, coupled with dendritic growth of the spongy ice matrix as a result of the external heat transfer. Early results show that the temperature of the impinging spray is a very important factor in promoting entrapment of the surficial liquid in the growing spongy matrix. Low temperature spray promotes supercooling in the liquid film, and stimulates aggressive dendritic ice crystal growth, thereby enhancing the sponginess.

Small ice accretion masses generally conform to the shape of the underlying surface. However, field observations show that large ice accretion masses can develop a highly convoluted configuration which may become quite decoupled from the shape of the underlying substrate. Traditional ice accretion models are unable to account for such geometrical complexity and the attendant increase in surface area, which can have a dramatic effect on the overall ice accretion rate. With a view to exploring this problem, Szilder and Lozowski (1994 a, b, c) have developed a random walk model of ice accretion which is capable of simulating ice accretion on objects of arbitrary three-dimensional geometry. This model as been used to simulate pendant ice formation, such as arrays of icicles, on cables and hemispherical bodies. Szilder et al. (1995) present an experimental verification of this model.

Collaboration between Kachurin, Kobos, Karev and Lozowski has led to the development of a new model of icing on a cylinder which takes into account the physical and hydrodynamical properties of the liquid film, and the effects of salinity. Using empirical correlations between such models and the total measured ice load, it is possible to employ them operationally to make marine icing forecasts.

The final icing model under development has been coupled with the National Research Council's Ship Dynamics Simulation Package in order to explore the effects of icing on vessel dynamics. This is a three-dimensional, time-dependent model which has been specifically designed for the stern trawler MT Zandberg, owned and operated by Fisheries Products International. It improves on our previous model for the U.S. Coast Guard Cutter Midgett in a number of respects which have to do with spraying, surface brine flow and model discretization. The model results show the susceptibility of this vessel to dynamic instability when heavy, asymmetrical ice loads are accreted with winds that are only slightly to port or starboard (Chung et al., 1995).

Forest and Lozowski have recently completed a series of icing wind tunnel experiments to examine the feasibility of using high frequency acoustic scattering to measure the thickness of marine ice accretions. At frequencies of 100 kHz to 1 MHz, we found that the attenuation was sufficiently strong over a few centimetres of path to preclude detection of the signal scattered from the surface of the accretion. While we do not understand the mechanism of this

attenuation, it has also been noted by Page et al. while investigating the propagation of high frequency sound through mixtures of polystyrene beads and water.

Atmospheric Refraction

Mr. Russell Sampson has completed his M.Sc. thesis entitled "Atmospheric Refraction and its Effects on Sunrise and Sunset." He measured the time of 244 sunrises and 125 sunsets and used them to determine the astronomical refraction of the Sun's upper limb at the moment of sunrise and sunset on a zero horizon. The mean astronomical refraction was found to be 0.669 degrees with a standard deviation of 0.175 degrees. The mean sunrise refraction was found to be about 20% higher than the mean sunset refraction, while the sunrise standard deviation was about twice the sunset standard deviation. Both the monthly mean refraction and its standard deviation reach a maximum during the colder months. Astronomical refraction is found to be strongly correlated with the surface temperature and the surface temperature lapse rate. The standard deviation of refraction is correlated with the standard deviation in the surface lapse rate. Anomalous refraction occurs with surface inversions. These are typically but not exclusively a cold weather phenomenon. The standard deviation of the monthly mean astronomical refraction appears to place severe restrictions on claims regarding the astronomical knowledge of Neolithic people. Specifically, the claims of Thom (1971), that Neolithic observers could determine the obliquity of the ecliptic to an accuracy of 0.01 degrees and determine the exact date of the solstice, have been brought into question. The results also suggest that the precise alignment of the Egyptian Pyramids with the cardinal points, could have been achieved using the azimuthal positions of summer solstice sunrise and sunset.

Climate Modelling

An atmosphere-ocean climate box model has been used to examine the influence of the primary climate feedbacks (surface albedo, atmospheric albedo, and emissivity) on the steady-state and time-dependent behaviour of the climate system. The model consists of three non-linear ordinary differential equations that are simplified forms of the first law of thermodynamics for the atmosphere and the ocean and the continuity equation for the atmospheric component of the hydrological cycle. In the model, energy is exchanged between the ocean, atmosphere, and space by short- and long-wave radiation and by sensible and latent heat. The mass continuity equation expresses the atmospheric liquid water content as a function of the evaporation rate from the ocean surface and the precipitation rate. The model is used to analyze cloud feedbacks, since the cloud radiative properties are expressed as a function of the atmospheric liquid water content. The model also simulates other hydrological cycle feedbacks, including the snow-ice albedo and water vapor feedbacks.

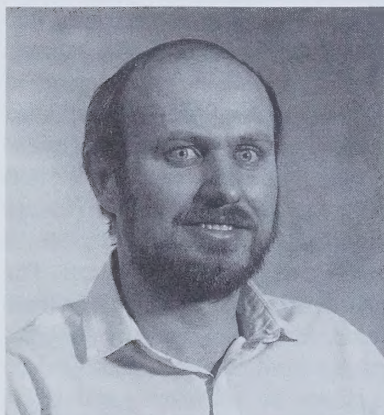
Feedbacks resulting from the atmospheric component of the hydrological cycle may lead to the occurrence of multiple climate equilibria in the model. The present equilibrium, which is stable, may coexist with other equilibria which may be stable or unstable. The model allows us to estimate the critical value of enhanced greenhouse warming which could lead to a climate transition between the present equilibrium and a considerably warmer, stable equilibrium. We consider the possibility and the circumstances under which such a catastrophic climate vacillation might occur.

Because of its simplicity, the present model provides insights into the climate system which would be difficult to gain from more complex models. Of course, the predictions of our simple model could and should be investigated further using a coupled atmosphere-ocean General Circulation Model.

6.4.3 Mesoscale Meteorology (Gerhard Reuter)

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Gerhard Reuter, Shucui Guan, Lingyan Xin, Bruno Larochelle, Raymond Beaubien



Gerhard Reuter

Analysis of Doppler weather radar-forecasting tornadoes

Larochelle and Reuter analyzed Carvel Doppler radar data using the Synthetic Dual Doppler (SDD) technique. This technique combines radial velocity measurements recorded at two different times by a single Doppler radar to synthesize the horizontal wind flow in a precipitating storm by interpreting the data as simultaneous measurements by two Doppler radars at different sites. The basic assumption is that the storm structure remains quasi-steady, yet moves fairly rapidly in the azimuthal direction. Numerical experiments of the SDD technique applied to a moving vortex with random errors superimposed on the Rankine flow pattern provided the following results:

1. The errors in the synthesized wind increase linearly with uncertainty of the Doppler velocities.
2. The errors in the synthesized wind are inversely proportional to the sine of the difference in storm viewing angles.
3. There is a bias to overestimate the actual wind speed.

Larochelle developed computer software to apply the SDD technique on mesoscale precipitating systems monitored by operational Doppler radars located at Carvel, Alberta. The SDD technique was found to be useful in identifying a roll circulation associated with a gust front sweeping across central Alberta. For the severe convective storm developing on 30 July 1993 over east-central Alberta, the SDD synthesized wind field indicated a vortex in the low level flow 90 minutes prior to the visual observation of a severe tornado that caused extensive damage in the Holden region. This case shows that proper use of the SDD technique can improve operational forecasting of tornado occurrence.

Effects of industrial pollution on cumulus convection

Guan and Reuter quantified the effects of pollution on cumulus development and rain showers. A numerical cloud model with bulk-water microphysics is used to simulate a cumulus developing in the polluted plume emitted from a large industrial plant. The pollution effects are included in the model by adjusting the cloud droplet concentration, the mass dispersion of the cloud droplet spectrum, and the supersaturation value required for cloud condensation. The cloud dimensions and updraft magnitudes of the simulated cumulus agree well with observations. Sensitivity experiments reveal that the pollution has only a minor effect on the cumulus development and the rainfall. Heavy pollution conditions cause an increase of accumulated rainfall by 1.8%, whereas light pollution indicates an even smaller rainfall enhancement of 0.2%. Using the Factor Separation Method these increases in rainfall can be attributed mainly to the mutual interaction of the supersaturation and the drop spectrum effects, while the individual contributions are very small.

Effects of mesoscale convergence on convective precipitation

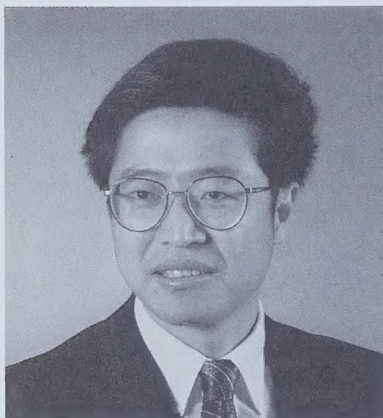
Xin and Reuter explored techniques to improve numerical predictions of convective storm development by incorporating wind estimates derived from Doppler radar observations. Of particular promise for severe storm initiation was the radar-derived profile of velocity convergence. An axi-symmetric cumulus model has been applied to simulate the convective storm development observed on 19 August 1992 over central Alberta. The model fields are initialized with the Stony Plain sounding of temperature and humidity and the convergence profile deduced by the VVP-method from the Carvel Doppler radar measurements. The simulated rainfall rates and rainfall accumulation values agreed well with field observations.

The effects of convergence on precipitation are quantified by a large number of sensitivity experiments with varying convergence magnitude, depth of convergence layers, and vertical distribution of the convergence magnitude. Increasing either the magnitude or the depth of the low-level convergence layer results in stronger convection and more rainfall at an earlier time. The variation of rainfall on depth is monotonous but nonlinear. The nonlinearity in rainfall enhancement is even more apparent when changing the depth of the convergence layer. A careful examination indicates that the convergence magnitude largely controls the convection growth in the early stages of the storm development, whereas the depth of the convergence is the important factor for the mature-phase of the storm.

6.4.4 Climate Analysis (Samuel Shen)

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Vlad Agapov, Yuanjie Yang, Xiaochun Wang, Lianger Gong



S. Shen

Spectral Approach to Estimate the Global Average Temperature

We considered the construction of a linear filter that optimally detects some forced climate signals, such as the global average of surface air temperature. This rather general scheme is expressed in terms of spectra (Empirical Orthogonal Functions and the corresponding eigenvalues) of the field to be detected. In particular, we constructed an optimal weighting scheme of using finitely many surface stations to measure the various orders of spherical harmonic components of the surface air temperature. The scheme is optimal in the sense that it yields the minimum mean square sampling error. While the zeroth order spherical component signifies the global average, the higher order components explain the regional climate variations (forced or natural). The idea of using the EOFs is based upon the mathematical principle of orthogonal projections from a space to its subspace which gives the best approximation. Our method makes obsolete the conventional approach which assumes an over simplified and usually not realistic correlation function. In addition, the computational scheme of our method is simple. An editor of *J. Climate* and some of the referees highly praised this "extremely important" contribution to the climate data analysis. The editor wrote "this work makes an important advance over previous studies involving optimal averaging in its consideration of inhomogeneous, anisotropic covariance structure. The continued use of obviously inappropriate assumptions about this structure will do nothing more than delay the optimum exploitation of existing historical data networks or the optimum design of the future ones. Your point about the relative insensitivity of error reductions to the exact shapes of the eigenvectors is extremely important". Two of this series of papers appeared in *J. Climate*, December 1994 and March 1995, respectively.

Estimation of Higher Order Spherical Harmonic Coefficients

We studied the problem of calculating the mean squared error (MSE) when estimating the spherical harmonic components of the surface air temperature field. The ratio of the MSE to the variance of the spherical harmonic component is expressed in terms of the length scale λ_0 , and the positions and weights of the measurement stations. The weights are optimized by the condition of minimizing the sampling error. At this stage of investigation, we assume the homogeneous statistics of the temperature anomaly field, and take the low frequency approximation (i.e., ignoring the time dependence). The spectra of the covariance of the

temperature anomaly are the coefficients of the Fourier-Legendre series of the covariance function. From a linear noise forced energy balance climate model, the spectra are analytically derived. Consequently, the MSE, the percentage sampling error, and the signal-noise ratio are computed for a given network of stations. Our results show that: (i) the sampling errors computed from both optimal weights and uniform weights increase with respect to the order of the spherical harmonic component, and (ii) the sampling errors computed from optimal weights are significantly smaller than those from uniform weights for sufficiently dense networks.

We regard Earth as a perfect sphere of unit radius. Let the surface air temperature field be denoted by $T(\hat{\mathbf{n}})$, where $(\hat{\mathbf{n}}) = (\cos \phi \cos \theta, \sin \phi, \sin \theta)$ is the unit vector pointing from the sphere's center to the point in question, and ϕ and θ are latitude and longitude respectively. The function $T(\hat{\mathbf{n}})$ can be expanded into spherical harmonics Y_{lm} :

$$T(\hat{\mathbf{n}}) = \sum_{l=0}^{\infty} \sum_{m=-l}^l T_{lm} Y_{lm}(\hat{\mathbf{n}}).$$

The spherical harmonic components T_{lm} are determined by

$$T_{lm} = \int_{4\pi} d\Omega T(\hat{\mathbf{n}}) Y_{lm}^*(\hat{\mathbf{n}}),$$

where Y_{lm}^* is the complex conjugate of Y_{lm} .

With about 60 reasonably positioned stations for sampling the spherical harmonic components T_{00} , T_{10} and T_{11} , one can get the sampling error below 10% when the optimal weights are applied. An experiment with 210 stations leads to the sampling error less than 10% for the spherical harmonic components from T_{00} up to T_{54} .

These results are included in two papers submitted to *J. Climate*.

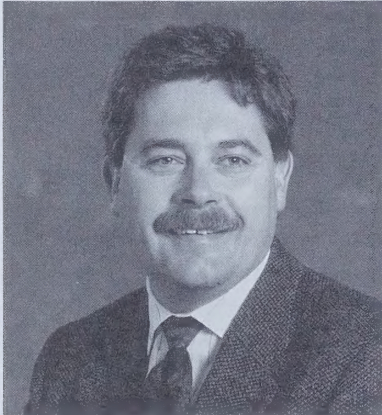
Modelling Toxic Mass Spreading

We considered the evolution of a toxic front influenced by a periodic external forcing. The forcing is due to some periodic changes of the surrounding conditions, such as the periodic release of chemical waste from a plant to the domain under investigation. If the system is at its resonant state, multiple oscillatory fronts may appear. The corresponding bifurcation diagram and the slope-stability criterion were obtained. This paper appeared in (Canadian Appl. Math. Quart.), summer, 1994.

Forced Evolution Equations

The two programs for the forced nonlinear Schrödinger equation and forced sine-Gordon equation are still under development.

6.4.5 Geophysical Fluid Dynamics (Gordon Swaters)
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G. Swaters

***Nonlinear Stability of Baroclinic Fronts in
a Channel with Variable Topography***

Richard H. Karsten and Gordon E. Swaters

The governing equations describing baroclinic bottom-trapped fronts in a channel with variable bottom topography are shown to be a noncanonical Hamiltonian system. The Hamiltonian formalism is exploited to derive a variational principle for arbitrary steady solutions based on an appropriately constrained energy functional. The variational principle is exploited to obtain formal and nonlinear stability conditions. In the infinitesimal amplitude limit, these stability conditions reduce to previously obtained normal mode results for the transverse gradient of the mean frontal potential vorticity.

***On the Hamiltonian Structure, Stability Characteristics
and Finite Amplitude Evolution of Geostrophic Fronts***

Carol G. Slomp and Gordon E. Swaters

A reduced gravity model with an outcropping interface developed by Cushman-Roisin is presented to describe the evolution of geostrophic fronts. This model describes a two layer system where only the uppermost layer is active and each outcrop line describes a front.

This model is found to possess a time invariant Hamiltonian. This Hamiltonian is used to show that all fronts described by this model are linearly stable. Nonlinear stability cannot be unconditionally established. However, a specific geostrophic wedge-like front is found to satisfy these conditions and thus found to be nonlinearly stable.

A weakly nonlinear wave packet theory is developed to describe the evolution of this wedge-like front using neutrally stable modes found by Cushman-Roisin. It is shown that the evolution of the wave packets is governed by the Nonlinear Schrödinger equation.

Solutions for the Nonlinear Schrödinger equation are found. The Stokes wave solution is also found to be modulationally stable. Plane wave solutions as well as a snoidal wave solution and a solitary wave solution are found. Further research areas are discussed.

Finite Amplitude Baroclinic Instability of a Mesoscale Gravity Current in a Channel

Curtis J. Mooney and Gordon E. Swaters

A weakly nonlinear theory is developed for the finite-amplitude evolution of marginally unstable modes for a mesoscale gravity current on a sloping bottom. The theory is based on a nonquasigeostrophic, baroclinic model of the convective destabilization of mesoscale gravity currents introduced previously which allows for large-amplitude isopycnal deflections while filtering out shear-based barotropic instabilities. Two calculations are presented. In the first, an amplitude equation is derived for marginally unstable modes not located at the minimum of the marginal stability curve. It is shown that the modes eventually equilibrate with a new finite-amplitude periodic solution formed. In the second, the evolution of a packet of marginally unstable modes located at the bottom of the marginal stability curve is described. The derivation of these two models is dramatically different due to fundamental differences in the mathematical properties of the leading order problems. In particular, it is shown that for the marginally unstable mode located at the bottom of the marginal stability curve, the entire gravity current forms a critical layer. It is shown that the leading order problem for the gravity current is nondispersive and is not coupled to the evolution of the overlying fluid and that these properties lead to an infinity of coupled amplitude equations. It is shown that if this system is truncated to include only the fundamental harmonic and its accompanying mean flow, there exist steadily-travelling solitary eddy solutions.

On the Stability Theory of Buoyancy-driven Ocean Currents over a Sloping Bottom

Richard H. Karsten and Gordon E. Swaters

In a previous paper, a new model was derived describing the baroclinic dynamics of buoyancy-driven ocean currents over a sloping bottom. In particular, a normal mode stability analysis and a general stability analysis based on an appropriately constrained energy invariant were presented. However, these two sets of stability results were not identical to each other. Here, we show that the normal-mode stability results previously described may be derived from a general stability analysis based on an appropriately constrained linear momentum invariant. In addition, we establish conditions for the nonlinear stability in the sense of Liapunov of these flows. The analysis presented here eliminates the need to introduce a Poincaré inequality between the perturbation energy and the enstrophy which the previous analysis was forced to assume. Relaxing this assumption means the present analysis is applicable to a much larger range of flow geometries and is therefore a substantially stronger result.

Stability Characteristics of Deep-Water Replacement in the Strait of Georgia

Richard H. Karsten and Gordon E. Swaters

It has been suggested that low-frequency current fluctuations in the southern Strait of Georgia are the result of baroclinic instability. However, data extracted from cyclesonde and fixed current meter moorings suggest that the conditions for baroclinic instability are highly variable in space and time. It has been recently discovered that there are summertime bottom-intensified gravity currents with fortnightly and monthly periods associated with the introduction of salty waters from the Juan de Fuca Strait during periods of neap tides. These currents are the dominant mechanism for deep-water renewal in the Strait of Georgia. It is argued that these currents are baroclinically unstable and that the stability characteristics are reasonably consistent with the observed structure of the low-frequency current fluctuations. The episodic nature of these unstable bottom flows may help to explain the spatial and temporal variability of the low-frequency current fluctuations observed in the Strait of Georgia.

***Gravity Currents Produced by Sudden Release of
a Fixed Volume of Heavy Fluid***

S.J.D. D'Alessio, T. Bryant Moodie, J.P. Pascal and G.E. Swaters

In this project we study various aspects of gravity (or density) currents arising from instantaneous releases of heavy fluids in a rectangular channel with a horizontal bottom. It is shown, by means of a scaling argument, that these plane currents can be successfully modelled by a two-by-two system in conservation form together with a pair of algebraic relations. A number of numerical experiments are carried out using this 'weak stratification' model in order to elicit information concerning the behaviour of gravity currents. A weakly nonlinear analysis is employed in order to clarify some aspects that were uncovered by the numerical experimentation.

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U.S. Geological Survey, Menlo Park

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